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The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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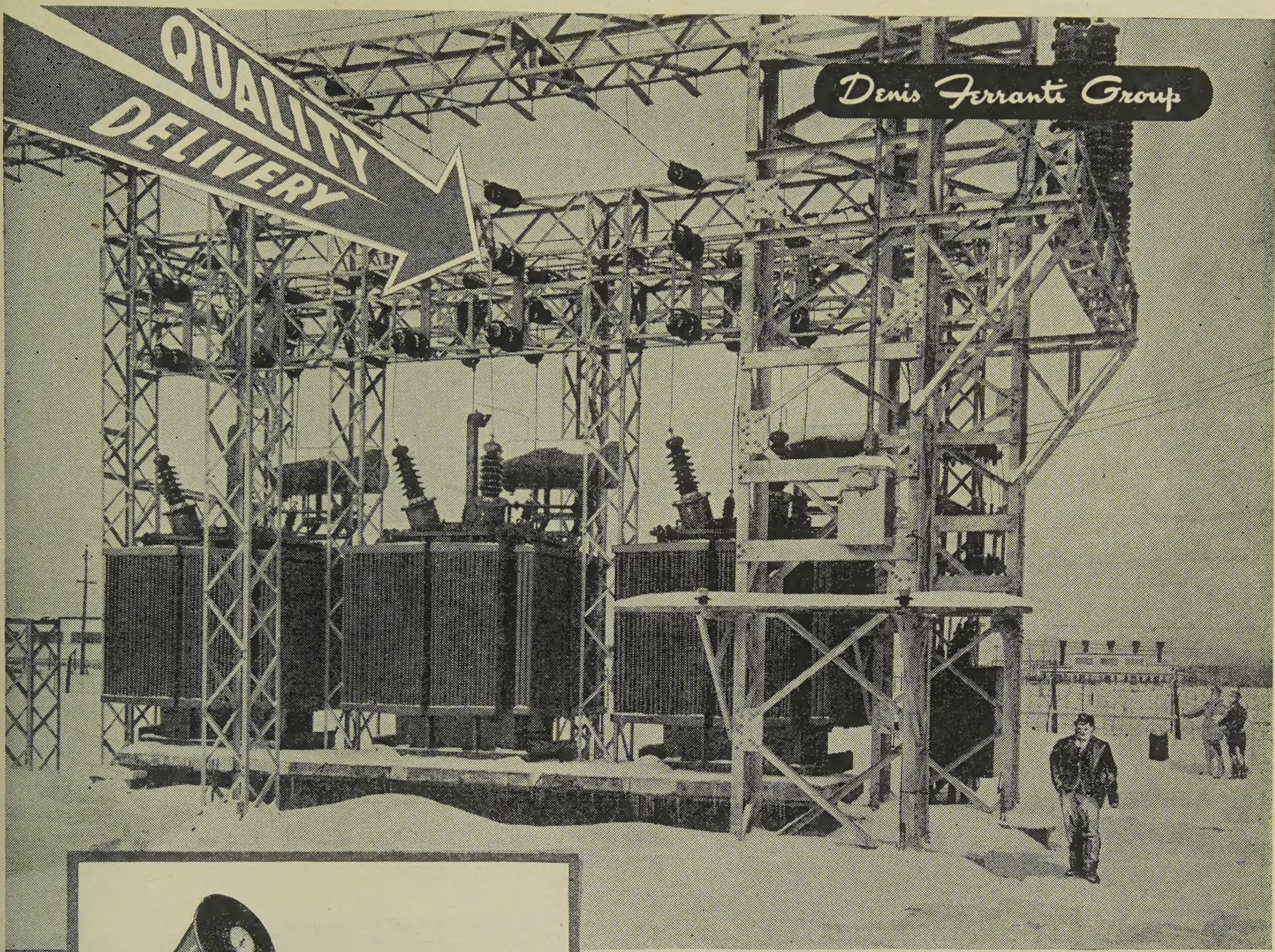
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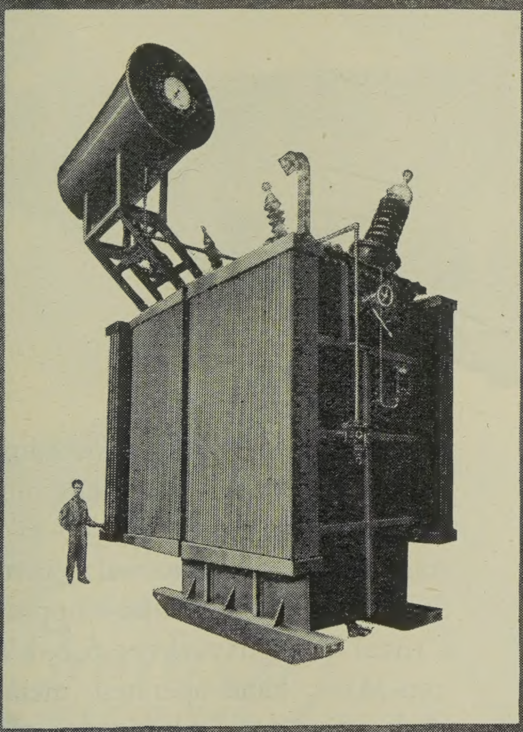

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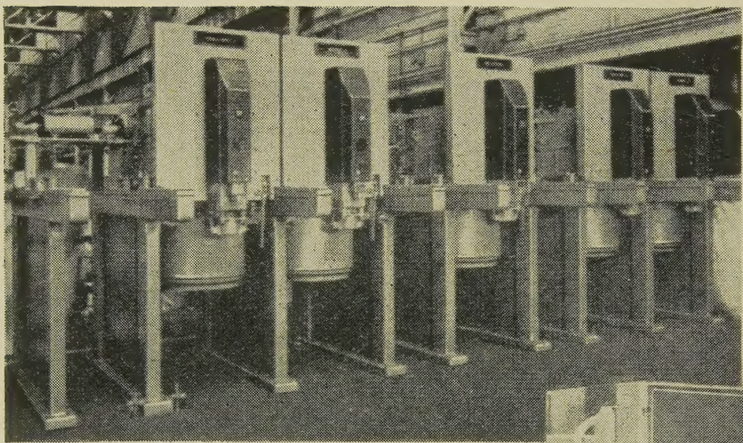
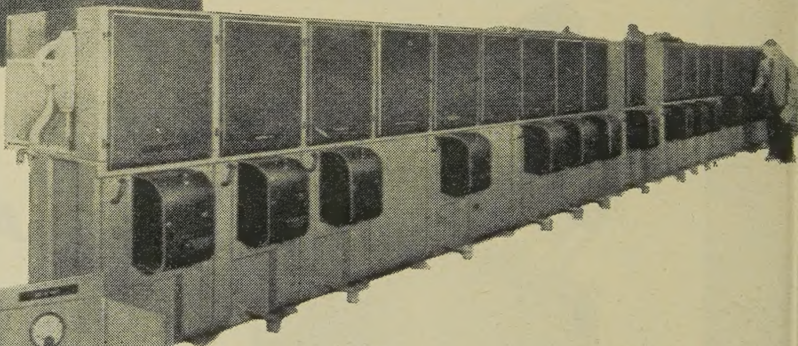


Five-panel, 22-kV, 500-MVA solenoid-operated switchboard for the control of the incoming feeders (from the Tata Power Co., Ltd.) and 7,500-kVA transformers which supply electric power to the whole refinery.



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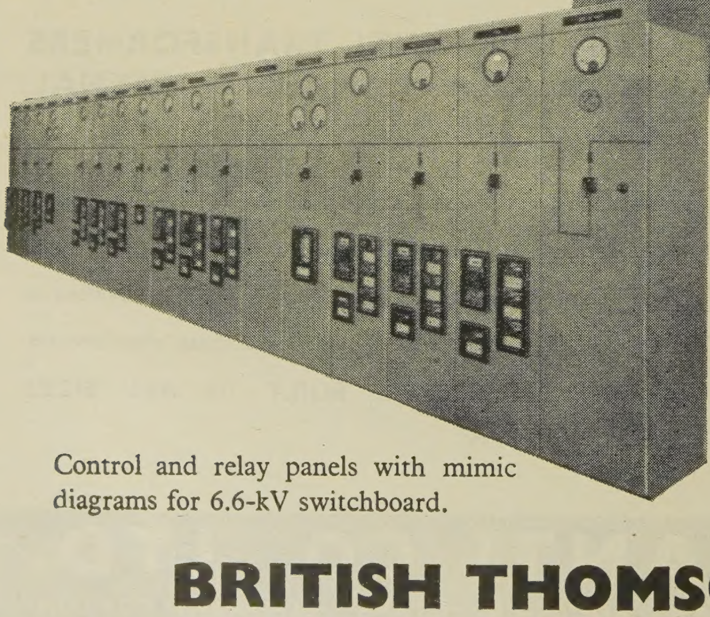

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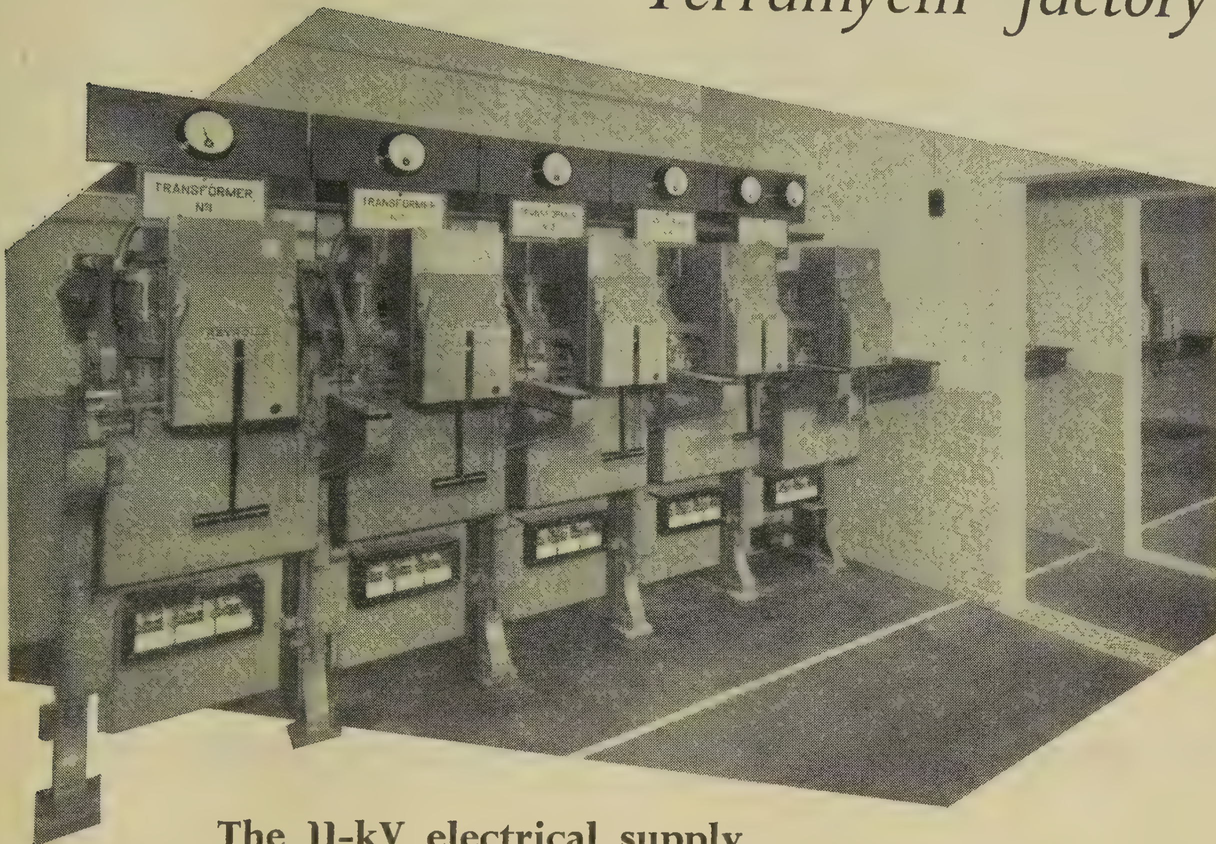

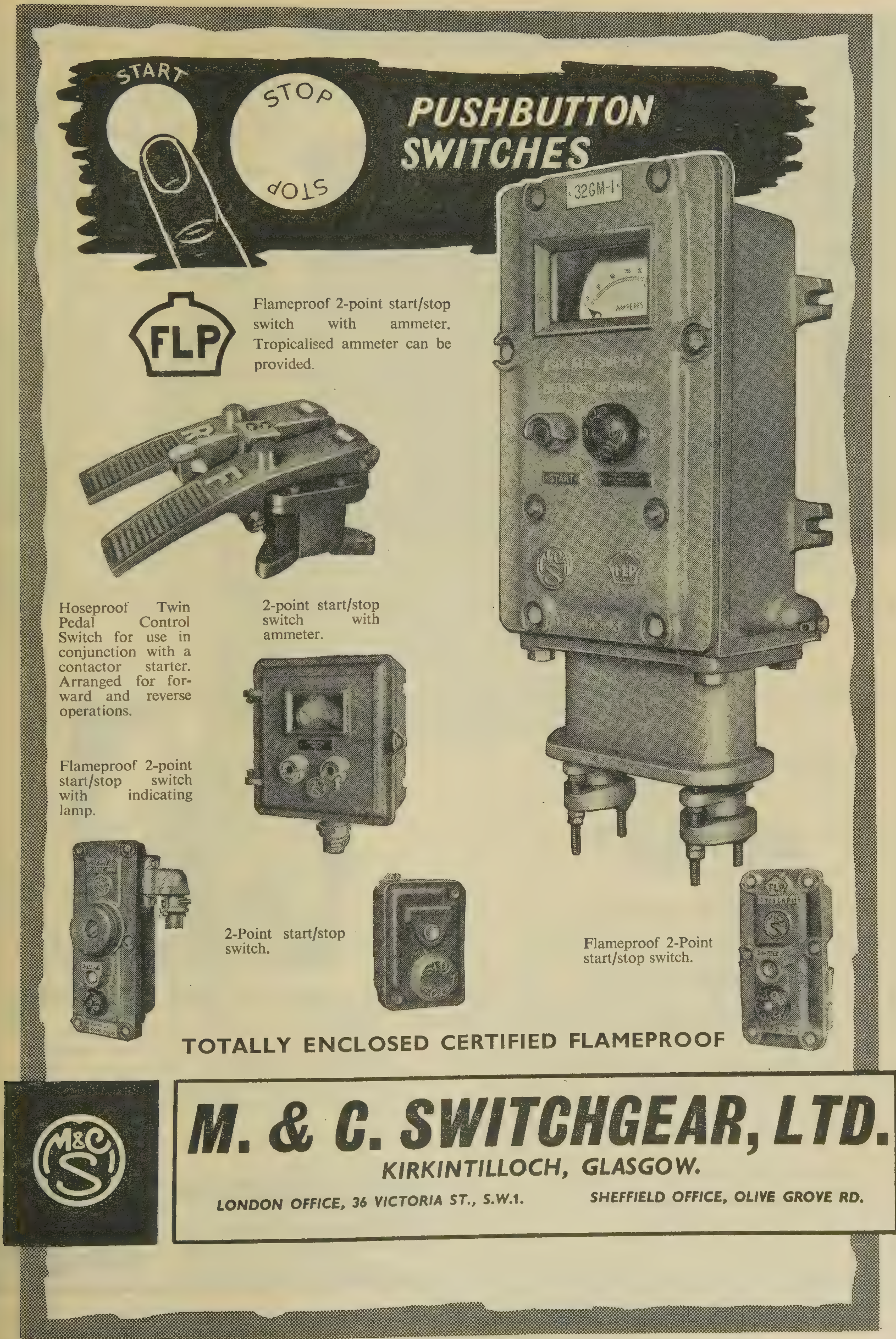
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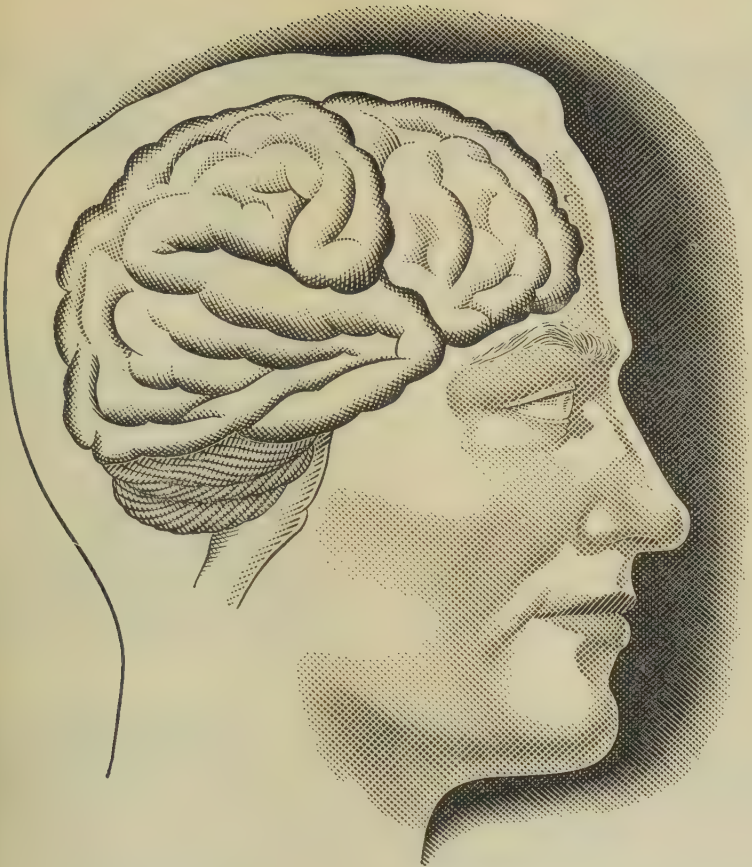

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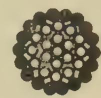

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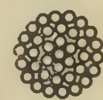

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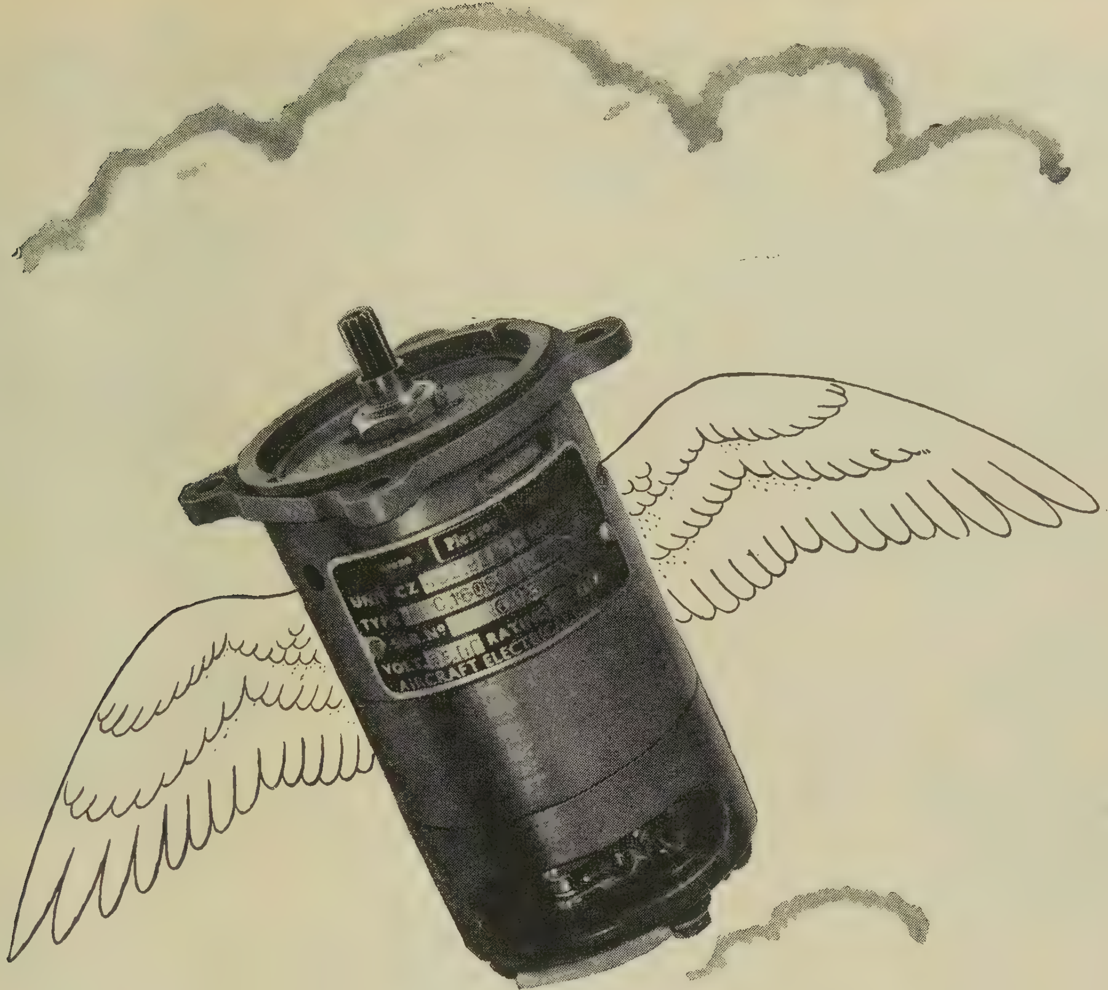

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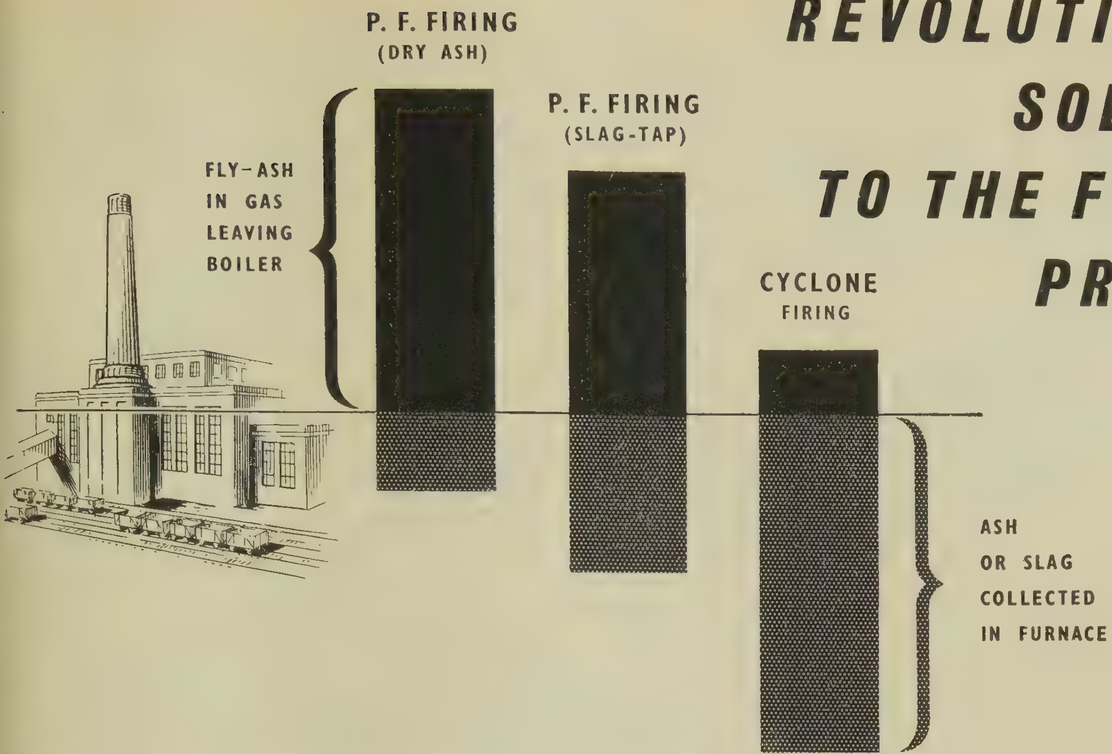

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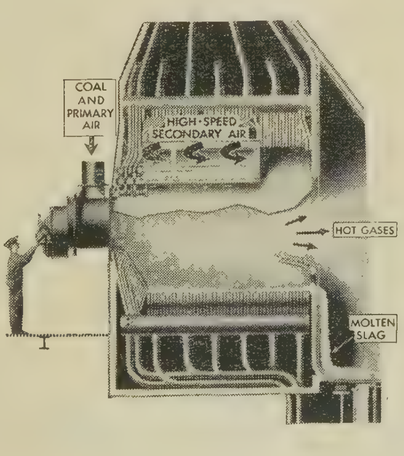

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VOL. 103. PART A. No. 10. AUGUST 1956

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Paper No. 2146 M
Aug. 1956

THE NON-DESTRUCTIVE TESTING OF ELECTRIC STRENGTH OF LIQUIDS

By W. P. BAKER, B.Sc.(Eng.), Associate Member.

(*The paper was first received* 20*th June*, 1955, *in revised form* 6*th March, and in final form* 17*th May*, 1956.)

SUMMARY

The development of an 80 kV breakdown testing equipment, designed for the non-destructive breakdown testing of liquids, is described. The equipment is so designed that, within one or two microseconds from the initiation of a breakdown, the source of high voltage is short-circuited by means of a special form of three-sphere gap, and consequently the energy dissipated in the breakdown path is little more than that stored in the self-capacitance of the electrode assembly.

The equipment is particularly suited to the testing of transformer oil, and about 5 000 breakdown tests have been carried out on one sample of oil without any evidence of the formation of carbon. Some data are included of test results obtained during a current programme of research into the mechanism of oil breakdown.

Provision has been made to enable the equipment to be transported easily as two units, one weighing about 2 cwt and the other 25 lb; this does not represent the minimum attainable size.

(1) INTRODUCTION

The wide scatter of results of breakdown tests on transformer oil, with the resulting need for many tests to be made, has led a number of workers to consider the possibility of making more than one test on the same filling. Rees and Edwards,* for example, quote several such tests, and, in common with other workers, they noted a change in the nature of the oil after the first breakdown. The change is believed to be due to the heat dissipation caused by the passage of the fault current and the resulting formation of free carbon in the oil.

When tests are being made with direct voltages up to about 25 kV, for which thyratrons are available, it is easy to chop the current within a microsecond or so of the start of the breakdown.† Furthermore, the theoretical limit to the resistance of the high-voltage source is very high, so that the energy dissipated in the breakdown path can be reduced to an insignificant value. Unfortunately, an alternating test voltage introduces certain complications, so that the solution devised by Watson and Higham,‡ although completely effective, is very elaborate. Nevertheless, the tremendous advantages of such equipment prompted an attempt to develop a simpler system to give the same results.

* REES, H. E., and EDWARDS, F. S.: 'Variations in the Electric Strength of Some Industrial Insulating Materials', *Proceedings I.E.E.*, Paper No. 1465 M, February, 1953 (100, Part IIA, p. 284).
† LEWIS, T. J.: 'Electrical Breakdown in Organic Liquids', *ibid.* Paper No. 1488 M, March, 1953 (100, Part IIA, p. 141).
‡ WATSON, P. K., and HIGHAM, J. B.: 'Electric Breakdown of Transformer Oil', *ibid. I.E.E.*, Paper No. 1501 M, March, 1953 (100, Part IIA, p. 168).

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Mr. Baker is with the Metropolitan-Vickers Electrical Co., Ltd.

(2) OUTLINE OF THE EQUIPMENT DEVELOPED BY WATSON AND HIGHAM‡

A schematic of the equipment developed by Watson and Higham at Birmingham University is shown in Fig. 1. The principle of operation is described by the authors as follows:

> The breakdown current through the test gap results in a voltage drop across the resistor R_4, which is amplified after sense correction, if necessary, to provide the firing pulse for the mercury thyratron. This results in the protective gap being triggered, the consequent reduction in the test-gap current then extinguishing the spark.

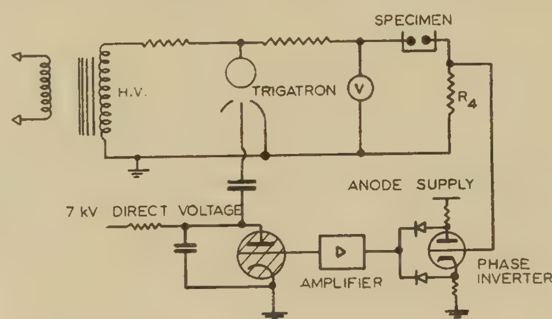

Fig. 1.—Protective circuit used by Watson and Higham.

This circuit has a few practical disadvantages, the most obvious of which is the complexity of the system with its need of auxiliary power supplies; a second important feature is the need for a high-energy triggering voltage to be applied to the trigatron.

(3) THE NEW TRIGGERING CIRCUIT

A considerable simplification was found to result when the testing equipment was designed round a symmetrical high-voltage system. The circuit is shown in Fig. 2, and schematically in Fig. 4. When the specimen is on the point of failure—presumably near a voltage maximum—the triggering capacitor C is charged to about $\frac{1}{2}V$ (where V is the peak test voltage), provided that the impedance of C at the supply frequency is large compared with R_1, r_1, and r_2. Immediately after failure, the test voltage is sustained by R_1 and R_2, so that the triggering electrode T is driven from zero potential to $-\frac{1}{2}V$ (relative to the centre tap of the transformer). The gap between this electrode and the earthy sphere S_e breaks down, and S_e itself reaches

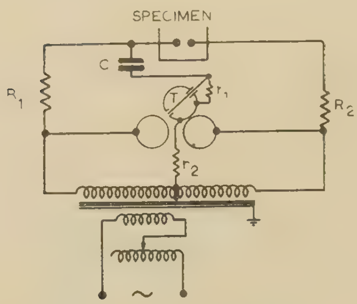

Fig. 2.—New protective circuit.

a potential of the order of $-\frac{1}{2}V$. The gap between S_E and the high-voltage sphere S_1, being now irradiated and slightly over-stressed, quickly fails, thus applying the full test voltage to the gap between S_E and the other high-voltage sphere, which, in turn, rapidly breaks down.

(4) COMPARISON OF PRESENT WITH BIRMINGHAM UNIVERSITY EQUIPMENT

In so far as both the original Birmingham University equipment and the present design incorporate a trigatron, it is desirable to examine their essential difference and show why the present equipment is preferred. Watson has stated that a simplification of his equipment, as shown in Fig. 3, operates, albeit at reduced

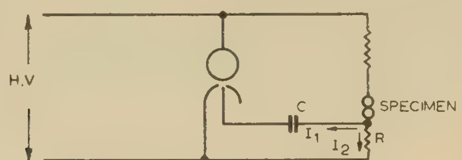

Fig. 3.—Simplification of circuit used by Watson and Higham, showing division of fault current.

efficacy. The energy required to irradiate the trigatron is obtained from the fault current through the specimen, which divides between R and C. In the present circuit, however, shown diagrammatically in Fig. 4, the condenser C is fully charged at

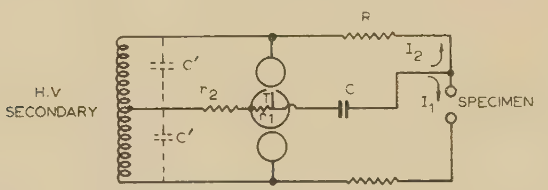

Fig. 4.—Division of irradiating energy in new equipment.

the instant of breakdown, and the energy irradiating the trigatron is drawn from this charge, only a part of which flows through the specimen, the remainder flowing back through the limiting resistor R and the self-capacitance C'.

In addition to this division of the irradiating current, there is a further advantage in that a useful part of the triggering voltage is added to the main voltage across the trigatron, so that the main gap is at a slight over-voltage during the time of irradiation.

(5) CONSTRUCTIONAL DETAILS

Two models of a chopped-voltage oil-testing set have been made, and both have been designed around an 80 kV (r.m.s.) 50 c/s centre-tapped transformer. In the first model, the trigatron was assembled from three 12·5 cm-diameter spheres, disposed one at each corner of an isosceles triangle. The triggering electrode was mounted in a brass insert in the face of one of th spheres; this sphere was constrained to move along the pe pendicular of the triangle, increasing the gap length as the voltag was raised. In the second model, shown in outline in Fig.

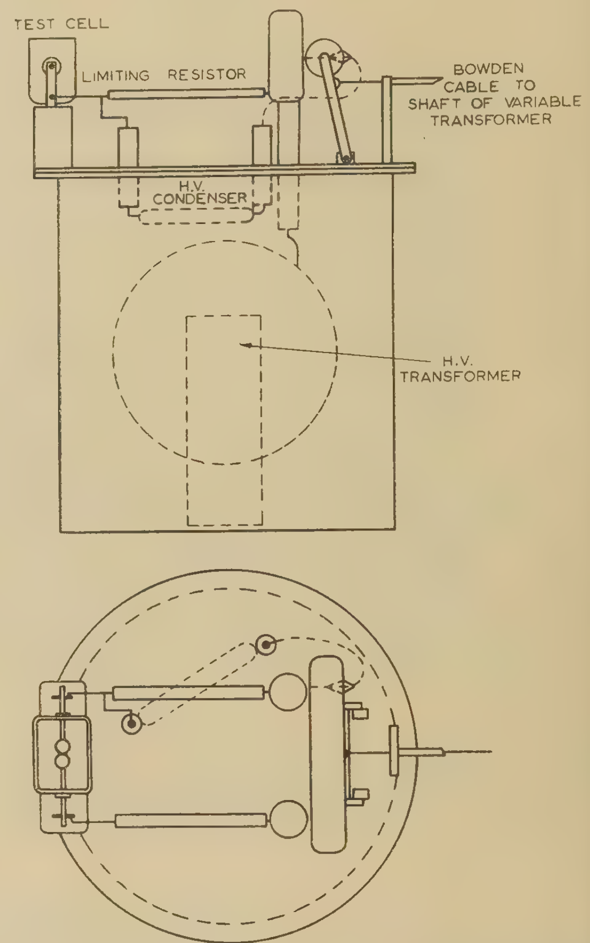

Fig. 5.—General arrangement of completed second model of choppe voltage oil-breakdown tester.

the spheres were replaced by three cylinders, 5 cm in diamete the two high-voltage ones, C_1 and C_2, being arranged verticall coaxial with the transformer bushings, and the third earth cylinder, C_E, being arranged horizontally. A small polystyren bushing, fitted to the back of the horizontal cylinder, carried th triggering electrode T, which projected to the front face of th cylinder, concentric with a small clearance hole drilled therei immediately facing one of the vertical cylinders C_1. As demo strated in Table 1, a sphere-gap may be replaced by crosse cylinders, the breakdown voltages—for spacings up to the ele trode radius—being the same within the accuracy of measuremen

In both models, the moving electrode was mounted on a fram pivoted at its bottom corners. As the voltage was raised, th electrode spacing was increased by means of a mechanical tran mission to the frame through a concentric cable from the sha of the variable transformer used to vary the primary voltage.

The test voltage was measured by means of a series-resistan type of high-voltage voltmeter, connected across one half of th transformer secondary, the resistance unit being mounted insi the transformer tank.

The 40 kV 7 $\mu\mu$F triggering capacitor was machined fro polystyrene rod, $1\frac{3}{4}$ in diameter, as shown in Fig. 6. In order

Table 1

COMPARISON OF BREAKDOWN VOLTAGES OF SPHERE AND CROSSED CYLINDER GAPS

Spheres and cylinders of 6·25 cm diameter

Spacing	Breakdown voltage, 50 c/s (peak)	
	Sphere gap	Cylinder gap
cm	kV	kV
0·5	17·2	17·4
1·0	31·9	31·4
1·5	45·9	45·2
2·0	58·2	58·2

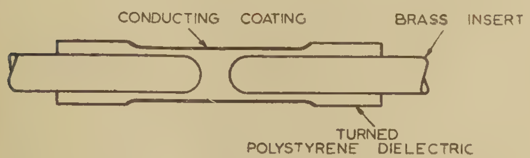

Fig. 6.—Section of polystyrene dielectric condenser.

reduce the dimensions of the high-voltage assembly, the whole of the top panel of the transformer tank was made from Perspex sheet.

(6) PERFORMANCE

The time-constant of the triggering network is 7 microsec; and it is therefore reasonable to assume that, if the short-circuiting action has not operated in, say, 4 microsec, it is unlikely to operate at all.

The energy discharged into the breakdown path from the self-capacitance of the electrode assembly is $\frac{1}{2}CV^2$ joules. The energy from the high-voltage source, dissipated in the breakdown path, is

$$\int_0^t \frac{V^2 r}{(R+r)^2} dt$$

where R = Source resistance, ohms.
r = Oil-breakdown-path resistance, ohms.
t = Time delay, sec.

The highest value that this latter energy could have would occur if r were constant and equal to R. With this substitution, the energy from the source becomes $V^2t/4R$ joules. The ratio of capacitance energy to maximum possible source energy, in the breakdown path, may be evaluated by substituting the following circuit values:

$$C = 5\,\mu\mu\text{F};\ t = 4 \times 10^{-6}\,\text{sec};\ R = 2\ \text{megohms}$$

Hence $$\frac{CV^2/2}{V^2t/4R} = 5$$

The calculation indicates that, even under the worst possible conditions, the energy supplied from the source is only about 20% of that supplied from the self-capacitance, C, of the electrode assembly. There is little advantage to be gained, therefore, from a reduction of the delay time below about 10 microsec.

(7) APPLICATION OF THE EQUIPMENT TO ELECTRIC-STRENGTH MEASUREMENTS OF TRANSFORMER OIL

The first model has been in use for routine electric-strength tests on transformer oil since the beginning of 1954, and has had the obvious advantage of enabling a high degree of polish to be preserved on the electrodes. Furthermore, the incidence of uncertain results, arising from spurious low breakdown strengths has been reduced to zero by the ability to make several repeat tests on a doubtful specimen.

Watson and Higham quoted an increase in electric strength of up to 100% during the first 100 breakdowns on a single specimen. Fig. 7 shows the variation of electric strength of a

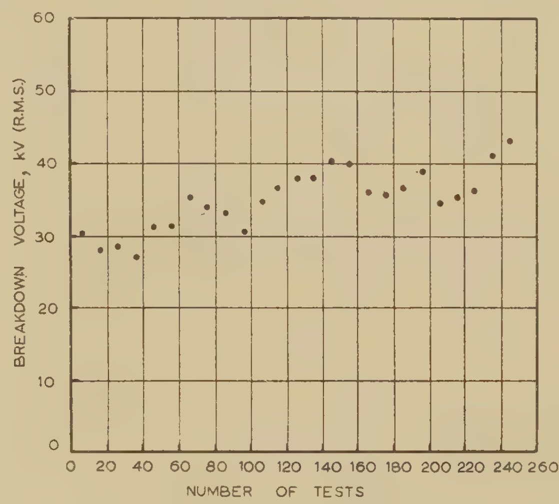

Fig. 7.—Variation of breakdown voltage during the course of 250 tests on a specimen of transformer oil.

specimen of transformer oil during the course of 250 tests with the present equipment. A small increase of electric strength with the number of tests is discernible, but it is not significant up to 100 tests. This increase—low compared with that observed by other workers—is attributed to the lower energy dissipation, resulting from the smaller self-capacitance of the test-cup assembly (less than 5 $\mu\mu$F). This evidence justifies the making of the repeat tests mentioned in the previous paragraph.

Apart from increasing the reliability of routine tests on transformer oil, the equipment has proved to be a particularly useful research tool, and the second model has been extensively used in this field.

One of the applications of the equipment has been to investigate the relation between breakdown voltage and time of stressing. Table 2 shows the results of tests on a sample taken straight from a tanker, and Table 3 shows the results after pumping the gas above the oil surface down to a pressure of 1 mm Hg for 16 hours. Table 4 shows the results on a filtered and degassed specimen of oil. There is a difference in the method of calculating the mean

Table 2

BREAKDOWN-VOLTAGE/TIME CURVE FOR SAMPLE OF TRANSFORMER OIL TAKEN FROM TANKER

Tested between 13 mm-diameter spheres, spaced 2·5 mm apart

Breakdown voltage	Mean time to breakdown
kV (r.m.s.)	sec
50 (mean of 20 tests)	(Voltage rapidly applied at 3 kV per second)
40	4 (mean of 10 tests)
35	5 (mean of 10 tests)
30	12 (mean of 10 tests)
25	32 (mean of 10 tests)
20	Over 300 (one test)

Table 3

BREAKDOWN-VOLTAGE/TIME CURVE FOR SAMPLE OF TRANSFORMER OIL TAKEN FROM TANKER AFTER CONDITIONING FOR 16 HOURS AT 1 MM HG AND 20° C

Tested at atmospheric pressure between 13 mm-diameter spheres spaced 2·5 mm apart

Breakdown voltage	Mean time to breakdown
kV (r.m.s.)	sec
56·5 (mean of 10 tests)	Rapidly applied at 3 kV per second
50	2 (mean of 10 tests)
45	9 (mean of 10 tests)
40	55 (mean of 10 tests)
35	99 (mean of 5 tests)
30	Over 300 (one test)

Table 4

BREAKDOWN-VOLTAGE/TIME CURVE FOR DEGASSED AND FILTERED OIL

Tested at 20° C and atmospheric pressure between 13 mm spheres spaced 1·5 mm apart

Time of stressing	Breakdown voltage	Number of tests
sec	kV (r.m.s.)	
1	43	35
2	43	17
3	44	14
4	44	11
5	41	7
6	40	5
8½	38	12
12½	44	12
16	40·5	12
26	34·5	11
40	37	11
58	42	11
81	36	11

values between the results in Table 4 and those in Tables 2 and 3. Where there was a marked time dependence (i.e. a steep breakdown-voltage/time characteristic) it was a simple matter to apply a fixed voltage to the specimen several times and calculate the mean time to breakdown. With the degassed and filtered specimen, however, a large number of tests was made over a range of voltages; the times to breakdown were noted and the results were grouped into small time intervals, the mean time and mean breakdown voltage being calculated for each group.

The results, given in Tables 2, 3, and 4, show that oil wi gas in saturated solution has a steep breakdown-voltage/tin characteristic, which becomes fairly flat after the oil has bee degassed and filtered.

With each breakdown test, a tiny bubble forms in the gap ar slowly rises to the surface. The volume of this bubble is abo 10^{-4} cm^3, and, by breaking down an oil specimen about 5 00 times, enough gas was collected to be analysed by means of mass spectrometer. Two such tests were made: one with sample taken direct from a tanker,* and one with a simil sample, after it had been degassed at a pressure of about 1 mm H and a temperature of about 120° C. These results are shown Table 5.

Table 5

ANALYSIS OF GAS EVOLVED DURING BREAKDOWN OF DF FIBRE-FREE TRANSFORMER OIL, BEFORE AND AFTER DEGASSIN

Constituent	Oil direct from tanker	After degassing
	% by volume	% by volume
Air	52	17
Excess nitrogen ..	11	9
Excess argon	0·2	0·2
Excess carbon dioxide	0·3	0·1
Water	33	5
Hydrogen	2·5	69

(8) CONCLUSIONS

An 80 kV (r.m.s.) testing set with fast short-circuiting of th test voltage has been developed, constructed, and used for ove two years. The equipment is simple and is reliable in operatio One model has been made which weighs less than 2 cwt and therefore reasonably portable.

The equipment has proved eminently suitable for routine c testing, since over 1 000 tests may be made without apprecia damage to the electrodes. It has also proved invaluable as research tool, because many breakdown tests may be made c one specimen, and a breakdown during a series of measuremen on other parameters is not serious.

(9) ACKNOWLEDGMENTS

The author wishes to thank Dr. Willis Jackson, Director Research and Education, and Mr. B. G. Churcher, Manager Research Department, Metropolitan-Vickers Electrical Co., Ltd for permission to publish the paper.

* The distinction is made between a specimen taken from an oil drum or simi storage vessel and one taken from a tanker, because the latter has been found to completely free from visible fibres and to be substantially drier. This is presuma due to the ease with which a large quantity of oil may be purified and maintained pu compared with that associated with small quantities (see, for example, BRAZIER, L. *Proceedings I.E.E.*, 1953, 100, Part IIA, p. 95).

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Feb. 1956

THE PENETRATION OF SURGE VOLTAGES THROUGH A TRANSFORMER COUPLED TO AN ALTERNATOR

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SUMMARY

Most modern transmission systems operate at 66 kV or higher voltage and are supplied from alternators whose voltage is stepped up by transformers, and when considering the effect of transmission-line lightning surges on a power station it is necessary to regard the transformer and alternator as a single unit.

After a brief analysis of the phenomena likely to be produced when an impulse voltage is applied to a transformer coupled to an alternator, the results are confirmed by tests on three such units. These show that the principal transfer of voltage through the transformer is due to magnetic coupling between windings and causes an oscillatory voltage to be superimposed on the surge voltage in the l.v. winding. In addition, the distributed capacitance and inductance between the windings of the transformer cause an electromagnetic transfer of voltage with travelling waves in both the transformer and alternator windings.

Approximate empirical methods are given to calculate the transformer l.v. voltages from the various circuit parameters. The results are compared with those obtained from the tests.

Since in practice the transformer and alternator are excited at power frequencies, whenever a surge is likely to reach the windings it is necessary to allow for this in estimates of the voltages which may occur at the alternator terminals. On the assumption that the surge protection for the unit consists of a rod-gap or other voltage-limiting device at the transformer h.v. terminals, an analysis is made with a view to ascertaining the maximum voltage which may occur at the alternator terminals. In a typical case this is shown to add about 10% to the potential expected without allowing for the power-frequency excitation.

LIST OF PRINCIPAL SYMBOLS

C = Effective capacitance of an alternator phase to earth.
C_g = Actual capacitance of an alternator phase to earth.
k = Transformer turns ratio.
k_1 = Transformer ratio [i.e. $\sqrt{(3)}k$].
k_2 = Transformer impulse transfer voltage ratio [i.e. (h.v. winding)/(l.v. winding)].
L = Effective inductance of transformer per phase.
l = Length of alternator winding per phase.
p = Mathematical operator.
t = Time.
$V\varepsilon^{-\alpha t}$ = Applied impulse voltage.
V_c = Alternator terminal voltage or voltage of equivalent capacitance.
V_p = High-voltage protection level on transformer.
V_1 = Transformer h.v. power-frequency voltage (r.m.s. line).
v = Alternator terminal voltage (to earth).
x = Distance along alternator winding from terminal.
α = Inverse time-constant used to define applied impulse voltage.
Z_1 = Alternator surge impedance.
Z_2 = Surge impedance of line connected to transformer.
β, γ, Δ = Inverse time-constants as defined in eqns. (3) and (4).
ω = Angular frequency, power frequency or as defined in Section 4.

Dr. Robinson is with C. A. Parsons and Co., Ltd.

(1) INTRODUCTION

It is now a common practice to generate electric power with an alternator at approximately 11 kV and then to transform it up to about 66 or 132 kV—the voltages at which the principal switching and distribution networks operate. This means that the majority of the surges must pass through a transformer to reach the machine terminals. Very little seems to have been published on the penetration of lightning surges through a transformer connected to an alternator, the majority of the literature dealing with either transformers or rotating machines.

Hunter and Dillow[1] give a general survey of American practice for the protection of alternators up to 1950. They recommend applying protection on the line side of the transformer and also an earth capacitance and surge arrester at the machine terminals. They give oscillograms of the voltages which occur at the alternator terminals when a surge is applied to one terminal of a coupled transformer.

In two more recent papers Neuve Eglise and Laurent[2] describe the voltages measured on two transformers each connected to an alternator on the French hydro-electric system. In one case the alternator and transformer were connected by 45 m of busbars, and in the other by 250 m of armoured cable. The authors showed that the surge penetrated the transformer in two components: the electrostatic transfer between the two transformer windings, which gave a short-duration voltage at the alternator terminals; and the magnetically induced voltage, which consisted of aperiodic and oscillatory components. When the transformer and alternator were separated by the 250 m of cable the electrostatic component became insignificant, owing to the large capacitance to earth of the cable.

Armstrong, Howard and Johnson,[3] and Abetti, Johnson and Schultz,[4] in two companion papers, deal with the propagation of surges through generator units consisting of an alternator and a step-up transformer together with associated cables. After describing tests on each separately, they deal with tests on a complete unit consisting of a 135 MVA alternator and 145 MVA transformer. They show that similar results may be obtained by replacing the circuit by a transient analyser network consisting of an inductance corresponding to the transformer reactance, and a π-connected LC network to replace the alternator. They state that the principal means of transfer of the surge through the transformer is magnetic, with the flux linking the whole winding. In the case tested the transferred voltage waveform was dead-beat, except for a few oscillations at the beginning which the authors ascribe to travelling waves. They analyse the equivalent circuit for an infinite rectangular surge approaching the transformer through a line of known surge impedance. The l.v. voltage, calculated assuming a non-oscillatory waveform, agreed with that measured on the test generator unit.

It is proposed in this paper to describe a series of tests to determine the mechanism of transfer of voltage through a transformer to a coupled alternator when an impulse voltage is applied to the transformer h.v. terminals. An attempt is also made to derive an empirical method for calculating the transformer l.v. voltage using easily determinable circuit parameters.

In order to estimate the maximum stresses which the transformer l.v. winding and alternator insulations may be required to withstand, it is also necessary to allow for the alternating voltage in the circuit. This is done in a further mathematical analysis.

The usual form of connection is shown in Fig. 1, where the transformer h.v. winding is star connected (with the neutral point frequently earthed) and the l.v. winding delta is connected to a star-connected alternator. This form of connection permits earthing of the h.v. busbar neutral and of the alternator neutral without inducing circulating currents. Protective gear may be installed at the neutral of the alternator if desired. The delta-connected winding of the transformer l.v. side prevents any third-harmonic voltage generated reaching the main transmission system.

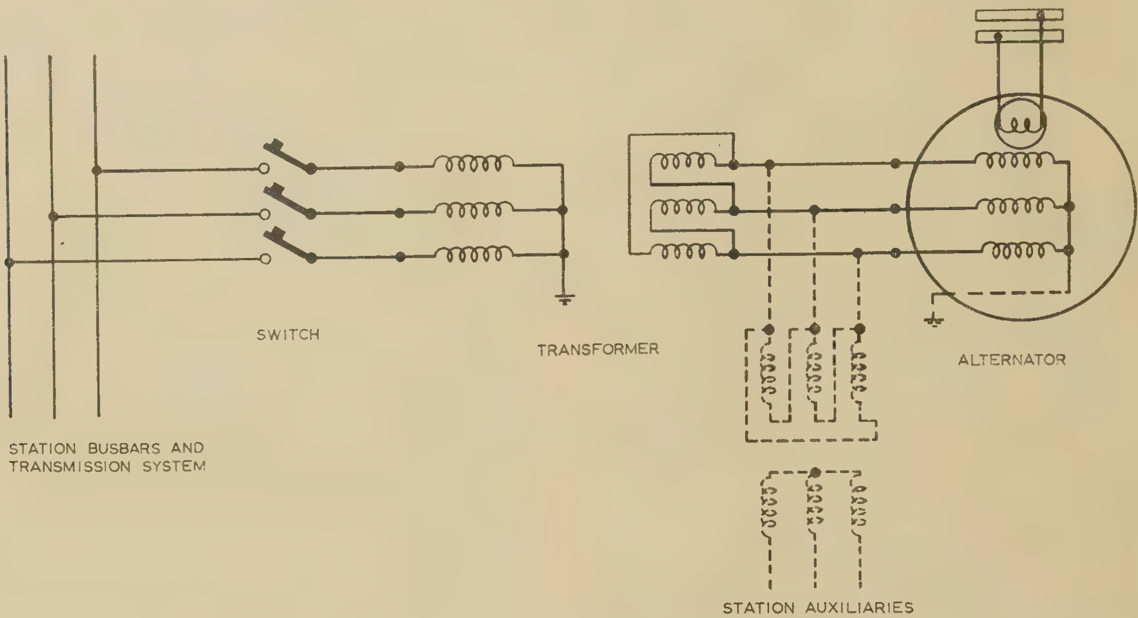

Fig. 1.—Simple circuit for a typical power-station generating unit.

(2) ANALYSIS OF THE PHENOMENA ANTICIPATED

The network described above and shown in Fig. 1 is an extremely complex system for rigorous mathematical treatment, since each winding has distributed circuit constants and the various interconnections between the transformer l.v. winding and the alternator give innumerable reflections of travelling waves. It is therefore proposed to divide the treatment into two sections: first, an approximate treatment of the circuit as a number of lumped parameters; and second, a brief description of the travelling-wave phenomenon which is superimposed on the lower-frequency oscillations.

(2.1) Equivalent Circuit with Lumped Parameters

A suitable equivalent circuit for considering the low-frequency oscillations has been suggested by Abetti, Johnson and Schultz.[4] They assume that the transformer leakage reactance is concentrated in an inductance (L) in series with each phase of the h.v. winding. The alternator is represented by a condenser (C) in parallel with a resistor (Z_1). At the same time a resistance (Z_2) is used to represent the surge impedance of the lines which are not impulsed. This substitution enables the circuit in Fig. 1 to be drawn as shown in Fig. 2 for single-, 2- and 3-phase impulses. It will be seen that the equivalent alternator terminals and neutral are represented in this Figure by the points R, Y, B and N respectively.

(2.1.1) **Single-Phase Impulse.**

From a consideration of Fig. 2(a) it will be seen that the impulse shown will induce a voltage in one limb of the transformer. The return path of the flux thus set up will induce voltages of half value and opposite polarity in the two other limbs and also on two alternator terminals (R and Y). The third alternator phase may be expected to remain approximately at earth potential, since its two ends are electrically equidistant from the points R and Y.

(2.1.2) **Two-Phase Impulse.**

From Fig. 2(b) it will be seen that in this case the impulse induces a main flux in two transformer limbs, with the return flux in the third limb. It would therefore be expected that equal and opposite voltages would be induced at terminals R and B of the alternator, while no voltage appeared at terminal Y. It might also be anticipated that the voltages induced in this case would be twice those produced by a single-phase impulse, but this, of course, depends on the voltage drop produced by the loading of the transformer l.v. winding by the alternator and is not borne out by the tests described later.

(2.1.3) **Three-Phase Impulse.**

Fig. 2(c) indicates that equal voltages will be induced in each l.v. winding of the transformer. Since the delta connection also imposes the condition that their total must be zero, each must be zero. Hence no induced voltages may be anticipated at the alternator terminals.

(2.2) Travelling-Wave Phenomenon

The complexity of the travelling-wave phenomenon prohibits a thorough analysis of the travelling waves. Makin[5] has shown that a surge is propagated through a transformer with two windings (assuming a disc type of coil) as two waves, one of which is characteristic of each winding, but which travel through both windings. In addition, there are waves which penetra

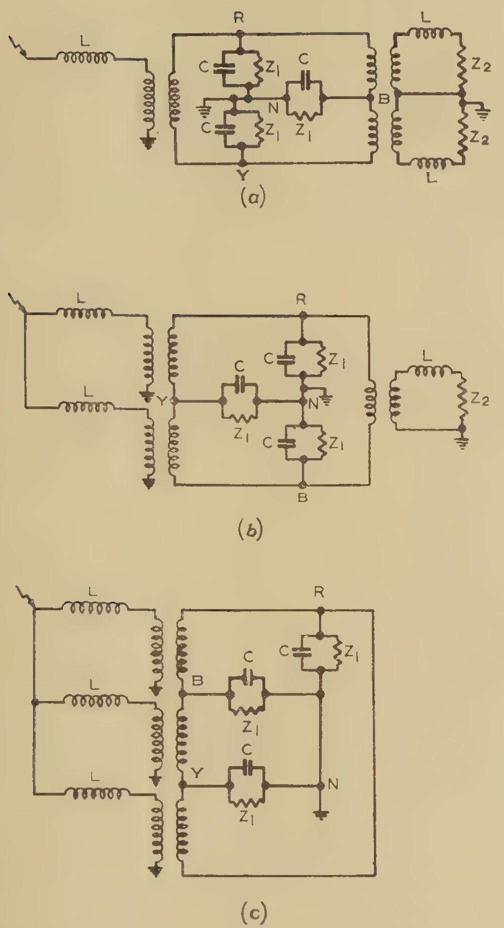

Fig. 2.—Equivalent circuits for impulse applied to a power-station generating unit consisting of an alternator and transformer.

the alternator winding as described by the author in a previous paper.[6] If a single-phase impulse is applied to the h.v. terminal of the transformer, as shown in Fig. 1, the waves in the l.v. network will contain

(a) Pairs of waves travelling through two transformer phases.
(b) Waves travelling through the corresponding phase of the alternator.

It will be clear that the subsequent reflection and refraction of these waves at the various junctions of the windings produces a very complex series of oscillations in the windings.

(3) EXPERIMENTAL INVESTIGATIONS

Two series of tests were carried out on transformers to check theoretical calculations. The first was to compare the theoretical and actual waveforms obtained using the circuits shown in Fig. 2. Since all the parameters except the transformer inductance could be measured easily, it was possible to confirm that similar waveforms were obtained if the transformer inductance was assumed to be equal to the short-circuit leakage inductance.

In the second series of tests actual alternators were connected to the transformers. Test results from three star-delta transformers are given in the paper, and the brief details of these and of the alternators used are as follow:

Transformer X: 70 MVA; 75·8/11 kV; reactance, 12·03%.
Alternator X: 50 MW; 11 kV; star connected.
The machine had two parallel windings per phase, which were connected at the terminals. These were of conventional design with strip end-connections. There were two poles, and the windings were distributed through 60 slots with two half-conductors per slot. The winding capacitance (actual) per phase was 0·14μF, and the surge impedance was 40 ohms [estimated from Reference (7)].
Transformer Y: 36 MVA; 141·6/11·8 kV; reactance, 12·39%.
Transformer Z: 18·75 MVA; 34·5/13·8 kV; reactance, 10·04%.
Alternator YZ: Both transformers Y and Z were tested when connected to a 30 MW 33 kV concentric-conductor alternator through a length of cable with an earth capacitance of 0·0333μF per phase. The alternator equivalent capacitance was 0·0205μF per phase and the surge impedance was 115 ohms.

(3.1) Tests on Transformer X and Alternator X

Tests on this set were carried out with a recurrent-surge oscillograph to record the voltages transferred to the alternator winding with single-, 2- and 3-phase impulse voltages applied to the transformer h.v. terminals. In addition, measurements were made to determine the voltage distribution in the alternator windings under these conditions, using the capacitance-tapping technique.[8] Typical results are given in Figs. 3–9. These consist of an oscillogram showing the relative magnitudes of the applied impulse and an l.v. terminal voltage, and a series of oscillograms taken with an increased applied impulse voltage to show the l.v. waveforms in greater detail. These show that, in general, the transferred voltages agree with the results previously described, namely that with single-phase and 2-phase impulses transferred voltages occur on two phases only, but with a 3-phase impulse the transferred voltage is only about 2½% of the applied impulse or about a quarter of that in the other cases. This is more than might have been anticipated, but is apparently due to the leakage flux. It will be noted that all transferred voltages contain a distinct ripple due to the reflection of travelling waves in the windings.

It may be noticed in Figs. 3 and 4 that slight differences exist between the initial voltages in phases R and Y. This is probably due to the transformer secondary winding being wound in two layers. One phase (R) is therefore connected to the upper layer and the other (Y) to the lower layer of the impulsed phase. As a result, the capacitance voltage distribution, which governs the relative magnitudes of the travelling waves, produces different potentials in the two ends of the winding.

(3.2) Tests on Transformers Y and Z and Alternator YZ

In both these cases oscillograms of the voltage transferred to the transformer l.v. terminals were taken. Drawings of typical oscillograms are given in Fig. 9, together with comparative calculated curves. These show phase relations between applied and transferred voltages similar to those obtained on transformer X.

(4) DERIVATION OF APPROXIMATE FORMULAE FOR THE VOLTAGES TRANSFERRED THROUGH A TRANSFORMER

The approximate circuits as given in Fig. 2 may be analysed theoretically, as shown in Section 11, using the Laplace transformation to solve the differential equations. Since the wavefront of the impulse wave does not affect the magnitude of the slow magnetically coupled oscillations it is possible to express the applied impulse by the formula $V\varepsilon^{-\alpha t}$. The transferred voltage may then be expressed by the equation

$$v=\frac{Vk}{L^2C}\left[\frac{Z_2-\alpha L}{(\beta-\alpha)(\gamma-\alpha)(\Delta-\alpha)}\varepsilon^{-\alpha t}+\frac{Z_2-\beta L}{(\alpha-\beta)(\gamma-\beta)(\Delta-\beta)}\varepsilon^{-\beta t}\right.$$
$$\left.+\frac{Z_2-\gamma L}{(\alpha-\gamma)(\beta-\gamma)(\Delta-\gamma)}\varepsilon^{-\gamma t}+\frac{Z_2-\Delta L}{(\alpha-\Delta)(\beta-\Delta)(\gamma-\Delta)}\varepsilon^{-\Delta t}\right] \quad (1)$$

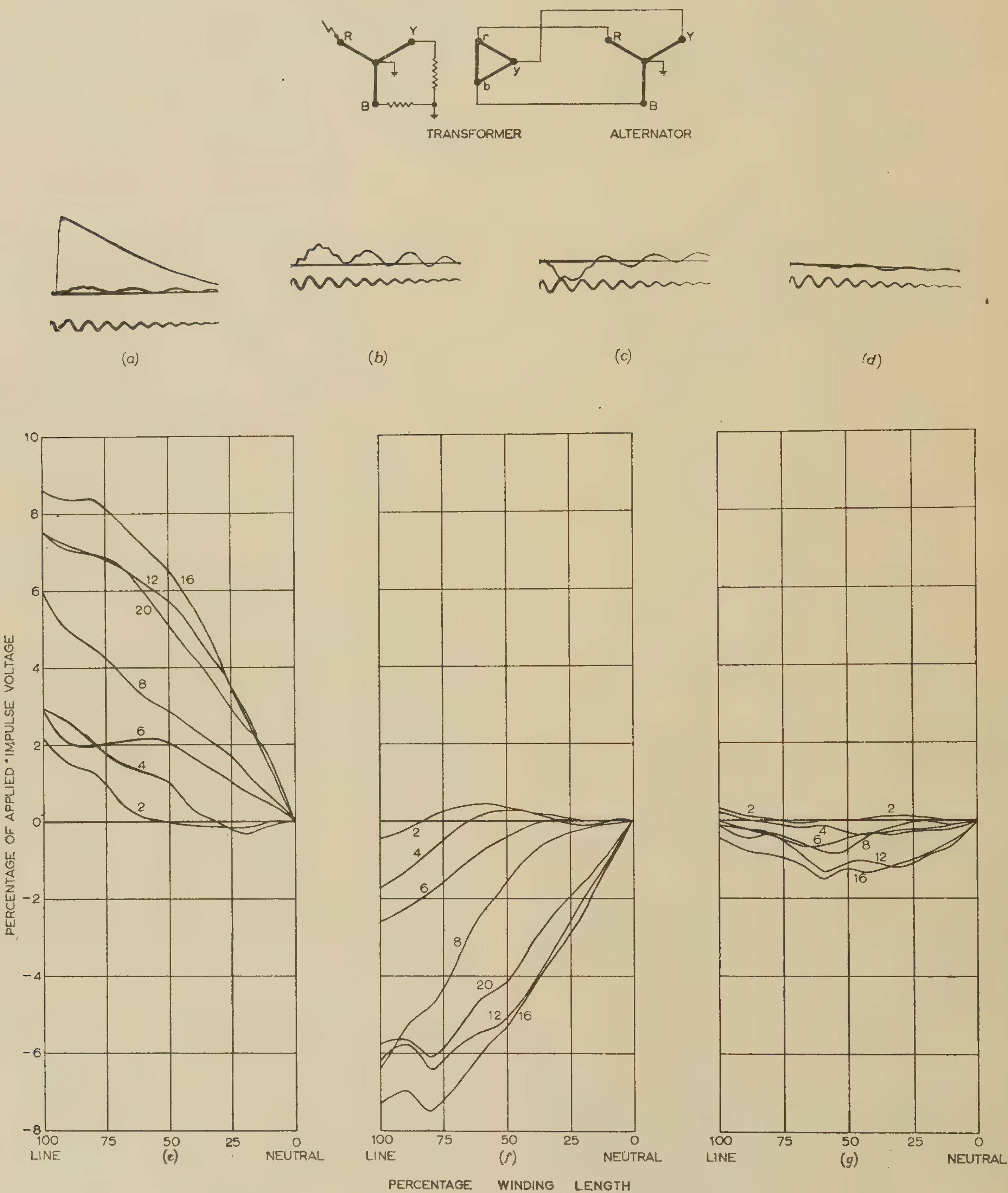

Fig. 3.—Impulse-voltage distribution in alternator winding, with the alternator neutral point earthed and the impulse applied to one phase of the transformer.

(a) Applied impulse, transformer terminal R and alternator terminal voltage phase R.

(b) Voltage on alternator terminal R, (c) Voltage on alternator terminal Y, (d) Voltage on alternator terminal B: with increased amplitude.

(e) Voltage distribution in alternator winding phase R.
(f) Voltage distribution in alternator winding phase Y.
(g) Voltage distribution in alternator winding phase B.

Applied impulse wavetail duration = 40 microsec.
Oscillator frequency = 100 kc/s.
Figures on curves indicate times in microseconds after application of impulse voltage.

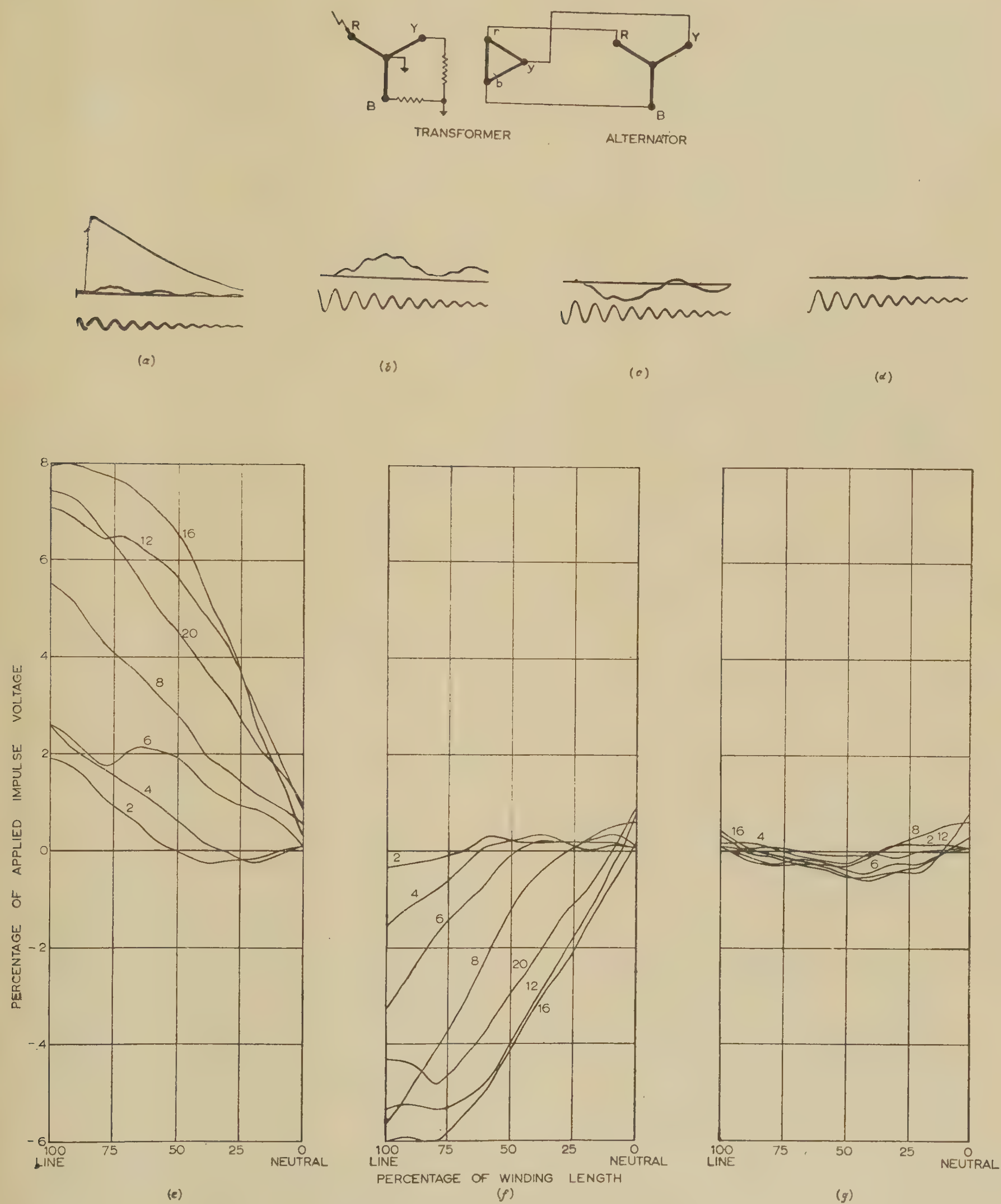

Fig. 4.—Impulse-voltage distribution in alternator winding, with the alternator neutral point isolated and the impulse applied to one phase of the transformer.

(*a*) Applied impulse, transformer terminal R and alternator terminal voltage phase R.

(*b*) Voltage on alternator terminal R }
(*c*) Voltage on alternator terminal Y } with increased amplitude.
(*d*) Voltage on alternator terminal B }

(*e*) Voltage distribution in alternator winding phase R.
(*f*) Voltage distribution in alternator winding phase Y.
(*g*) Voltage distribution in alternator winding phase B.

Applied impulse wavetail duration = 41 microsec.
Figures on curves indicate times in microseconds after application of impulse voltage.

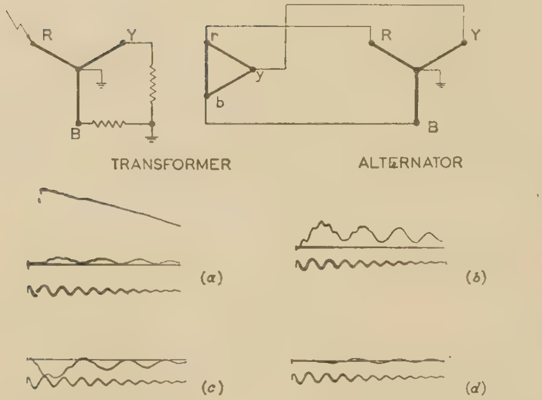

Fig. 5.—Voltages with single-phase impulse, alternator neutral point earthed.

Impulse wavetail = 110 microsec.
Oscillator frequency = 100 kc/s.
(a) Transformer h.v. phase R and alternator phase R.
(b) Alternator phase R.
(c) Alternator phase Y.
(d) Alternator phase B.
Note: impulse amplitude is greater for oscillogram (b) than (c) and (d).

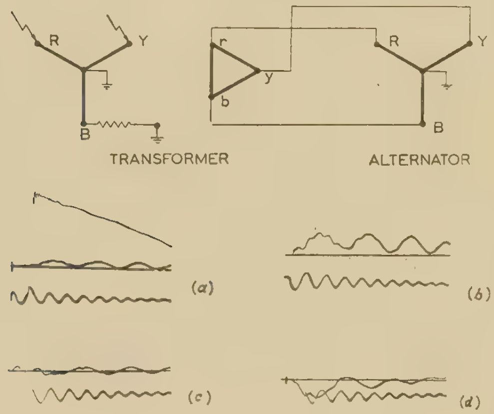

Fig. 6.—Voltages with 2-phase impulse, alternator neutral point earthed.

Impulse wavetail = 70 microsec. Oscillator frequency = 100 kc/s.
(a) Transformer h.v. phases R and Y and alternator phase R.
(b) Alternator phase R.
(c) Alternator phase Y.
(d) Alternator phase B.

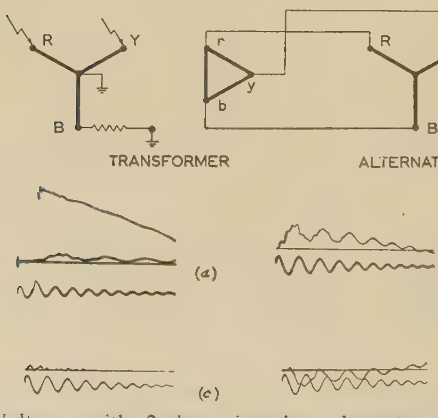

Fig. 7.—Voltages with 2-phase impulse, alternator neutral point isolated.

Impulse wavetail = 70 microsec.
(a) Transformer h.v. phases R and Y; alternator phase R: oscillator frequency = 100 kc/s.
(b) Alternator phase R
(c) Alternator phase Y } Oscillator frequency = 50 kc/s.
(d) Alternator phase B

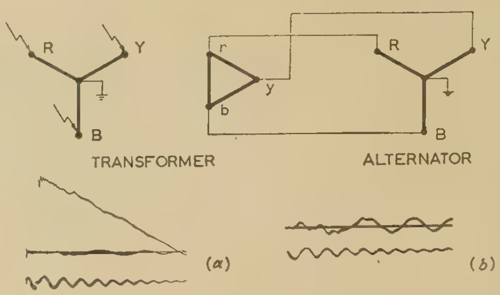

Fig. 8.—Voltages with 3-phase impulse, alternator neutral earthed

Impulse wavetail = 45 microsec.
(a) Transformer h.v. and alternator terminals: oscillator frequency = 200 kc
(b) Alternator terminal voltage: oscillator frequency = 100 kc/s.

Or

$$v = \frac{Vk}{L^2C}\left[\frac{1}{\beta-\alpha}\left\{\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2}\varepsilon^{-\alpha t} - \frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\varepsilon^{-\beta t} - \left[\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2} - \frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\right]\varepsilon^{-\gamma t}\cos\omega t\right\} + \frac{Z_2[\alpha\beta-\gamma(\alpha+\beta-\gamma)-\omega^2]-L[\alpha\beta\gamma-(\gamma^2+\omega^2)(\alpha+\beta-\gamma)}{\omega[(\gamma-\alpha)^2+\omega^2][(\gamma-\beta)^2+\omega^2]} \times \varepsilon^{-\gamma t}\sin\omega t\right] \quad . . . .$$

where $(p+\beta)$, $(p+\gamma)$ and $(p+\Delta)$ are the three real facto or $(p+\beta)$ and $[(p+\gamma)^2+\omega^2]$ are the real and comple factors of the expressions

$$p^3 + p^2\left(\frac{Z_2}{L} + \frac{1}{CZ_1}\right) + \frac{p}{LC}\left(\frac{Z_2}{Z_1} + 3k^2\right) + \frac{2k^2Z_2}{L^2C} \quad . \quad ($$

for a single-phase impulse or

$$p^3 + p^2\left(\frac{Z_2}{L} + \frac{1}{CZ_1}\right) + \frac{p}{LC}\left(\frac{Z_2}{Z_1} + 3k^2\right) + \frac{k^2Z_2}{L^2C} \quad . \quad ($$

for a 2-phase impulse.

Abetti and others[4] have found it suitable to take Z_1 and Z as being equal to the alternator and line surge impedances. C the assumption of a uniform distribution of voltage in tl alternator winding, as shown by Figs. 3 and 4, it is proved Section 11.1.4 that to store the same energy a simple capacit of one-third of the winding capacitance would be require This was therefore taken as the equivalent alternator capacitan of a conventional machine. A similar principle, though wi slightly more complex calculation, was employed for the co centric-conductor machine. The capacitance of any cab between the alternator and the transformer was merely add to the equivalent alternator capacitance.

(4.1) Method I: "Dead Beat Solution"

The curves obtained by plotting the above equations were non-oscillatory, or appeared to be so, owing to the very rap damping of the oscillatory component. The amplitude was al observed to be approximately one-half of that measured, owi to the power dissipated in the resistors of the equivalent circ representing the line and alternator surge impedances. practice the circuit would, in effect, contain only distribut inductance and capacitance, which, while having the dimensio of resistance, would not dissipate power. Study of the equati and the curves suggested two methods to obtain an appro

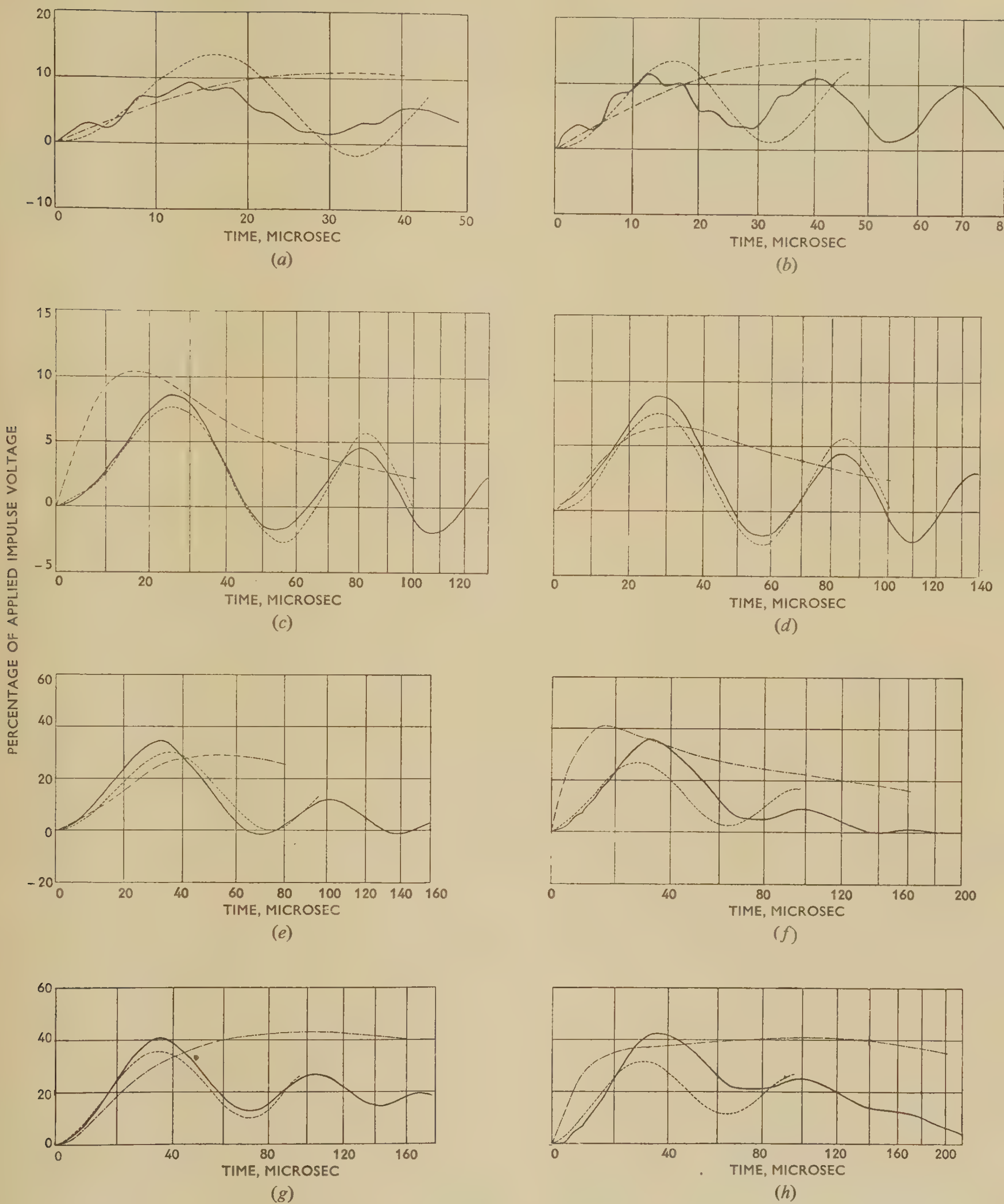

Fig. 9.—Calculated and test oscillograms of transformer l.v. terminal voltages with alternator neutral point earthed.

———————— Test oscillogram.
—·—·—·—·—·— Calculated voltage: dead-beat solution.
– – – – – – – – Calculated voltage: oscillatory solution.

(*a*) Single-phase impulse; transformer X; wavetail = 40 microsec.
(*b*) 2-phase impulse: transformer X; wavetail = 70 microsec.
(*c*) Single-phase impulse: transformer Y; wavetail = 43 microsec.
(*d*) 2-phase impulse: transformer Y; wavetail = 43 microsec.
(*e*) Single-phase impulse: transformer Z; wavetail = 47·5 microsec.
(*f*) 2-phase impulse: transformer Z; wavetail = 32 microsec.
(*g*) Single-phase impulse: transformer Z; wavetail = 172 microsec.
(*h*) 2-phase impulse: transformer Z; wavetail = 76 microsec.

mately correct value for the transferred voltage. The simplest was merely to double the actual voltages calculated, thus allowing for the oscillatory component to have a 100% overswing above the dead-beat curve. The curves thus obtained are shown by a dot and dash line in Fig. 9, the full line representing a tracing of the oscillograms taken on the transformers.

(4.2) Method II: "Oscillatory Solution"

The second method attempts to eliminate the mathematical term causing the major portion of the damping and then to plot an approximate waveform. As shown in Section 11, the solution of the transformed equation [eqn. (18)] demands the factors of the cubic in eqn. (3). Experience shows that one factor of this expression is approximately

$$\beta \simeq \frac{\dfrac{2k^2Z_2}{LC}}{\dfrac{1}{LC}\left(\dfrac{Z_2}{Z_1} + 3k^2\right)} = \frac{2k^2Z_2}{\dfrac{Z_2}{Z_1} + 3k^2} \quad . \quad . \quad . \quad (5)$$

for a single-phase impulse and one-half of this for a 2-phase impulse. The remaining factors may be expressed as

$$p^2 + Pp + Q \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The coefficients P and Q are, very approximately,

$$P \simeq \frac{Z_2}{L} + \frac{1}{CZ_1} - \beta \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$Q \simeq \frac{1}{LC}\left(\frac{Z_2}{Z_1} + 3k^2\right) \quad . \quad . \quad . \quad . \quad . \quad (8)$$

In order that the transferred voltage may be oscillatory the quadratic eqn. (6) must have factors of the form

$$(p + \gamma)^2 + \omega^2 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where γ is the factor determining the damping and is equal to $\frac{1}{2}P$. This contains the term $1/CZ_1$, which shows that the greater the resistance Z_1 the less the damping of the oscillations (as would be expected on practical grounds). Also, from a consideration of the transformer-alternator circuit and the approximate circuit, the resistance Z_1 is the principal source of power loss. To reduce this damping the term $1/CZ_1$ was subtracted from P, so the effective expression became

$$p^2 + \left(P - \frac{1}{CZ_1}\right)p + Q \quad . \quad . \quad . \quad . \quad (10)$$

The factors of this expression, when expressed in the form of eqn. (9), then provide the constants to substitute in eqn. (2). The resultant waveforms are shown by a broken line in Fig. 9.

(4.3) Method III: "Transformer Ratio"

Neuve Eglise[2] suggests that the voltage at the alternator terminals may be obtained from the applied surge voltage by assuming that the transformer ratio (i.e. line-to-line voltages) holds for the surge voltage. This method has the advantage of greater simplicity compared with the others, but it does not permit an allowance to be made for cable capacitances or for impulse waveform.

(5) COMPARISON OF CALCULATED AND TEST RESULTS

As stated in the last Section, Fig. 9 shows test and calculated transferred voltages at the transformer l.v. terminals. These indicate that the (broken) calculated curves approximate as closely as might be expected to the test waveforms. The relati maximum voltages, which are the factors governing the possib breakdown of the insulation, are given in Table 1.

Table 1

Fig. No.	Transformer	Number of phases impulsed	Maximum voltage to earth, percentage of applied impulse			
			Test results	Dead-beat method	Oscillatory method	Transferred ratio metho
			%	%	%	%
9(a)	X	1	9·5	10·9	13·7	14·5
9(b)	X	2	11·6	14	13·6	14·5
9(c)	Y	1	8·6	10·5	7·7	8·3
9(d)	Y	2	8·9	6·6	7·6	8·3
9(e)	Z	1	34·4	29	30	40
9(f)	Z	2	36	41	27	40
9(g)	Z	1	41	43	35·5	40
9(h)	Z	2	42	41	31·5	40

These results show an approximate agreement between th test results and calculated values. If the test results are assume to be correct the dead-beat method of calculation appears t give the most accurate results, since its largest error is 26%. O the other hand, the oscillatory method gives the closest approxi mation to the waveform obtained. It may be mentioned tha for the higher transformer ratios likely to be met in practice th "error" in the calculated transferred voltage represents only few per cent of the applied impulse. It should also be mentione that the accuracy of the test results was probably not more tha 1 or 2% of the applied impulse voltage.

The last column in the Table gives the transferred voltag obtained by dividing the applied impulse by the line-to-lin transformer ratio. This method of calculation cannot be con sidered to have the theoretical basis of the other methods, bu it does appear to give results of comparable accuracy. Thi may be accidental or it may be due to the fact that large change of load do not produce much variation of the l.v. voltage However, it has the advantage of greater simplicity.

(6) EFFECT OF THE 50 c/s EXCITATION ON THE STRESSE PRODUCED BY A SURGE

The transference of the surge voltage through a star-delt transformer has already been considered. However, in servic the transformer-alternator set would also have a 50 c/s voltag on the windings at the time of the surge. Hence the total stresse produced in the windings would be the sum of those produce by the surge and the 50 c/s voltage separately.

In order to limit the surges which may enter a station it usual to fit some form of voltage-limiting device, such as a roo gap, at the h.v. terminal of the transformer. The maximum surge voltage which this will permit to enter the transforme will depend on the point of the 50 c/s wave at which the surg occurs; for the transformer h.v. winding it will obviously occu when the 50 c/s voltage is at its maximum value of the opposit polarity. However, this is not the surge which will cause th maximum voltage stress at the transformer l.v. terminal, an thus in the coupled alternator, owing to the 50 c/s phase displace ment between the h.v. and l.v. terminal voltages in a star-delt transformer. The alternator voltage, however, may be derive either graphically or mathematically, as shown in Section 6. The former method is easier to understand, but the latter give a formula which permits the simpler evaluation of the maximum stress.

(6.1) Derivation of the Maximum Voltage which may Occur at the Transformer L.V. Terminals

The maximum voltage which may occur at the transformer l.v. terminals with a given protective level at the h.v. winding terminal may be derived graphically as follows. (The mathematical analysis is given in Section 11.2.) Let Fig. 10(*a*) represent one cycle of the transformer h.v. terminal voltage, $V_1/\sqrt{3}$, to earth on the phase considered, i.e. phase R. If the protective gap at this terminal is set to flash over at a voltage V_p, the maximum surge voltage which may occur at the terminal will be $V_p - V_1(\sqrt{2}/\sqrt{3})$, as shown in Fig. 10(*b*). It is assumed here that the maximum surge which will not be modified by the voltage-limiting device will be equal to the minimum voltage which will cause it to operate. This may be justified on account of the operating-voltage variations which occurs with these devices. The value of this clearly varies with the point of the cycle at which the surge occurs, for the latter can be regarded as taking place almost instantaneously. If the ratio of impulse voltage which will be transferred to the secondary is known, as

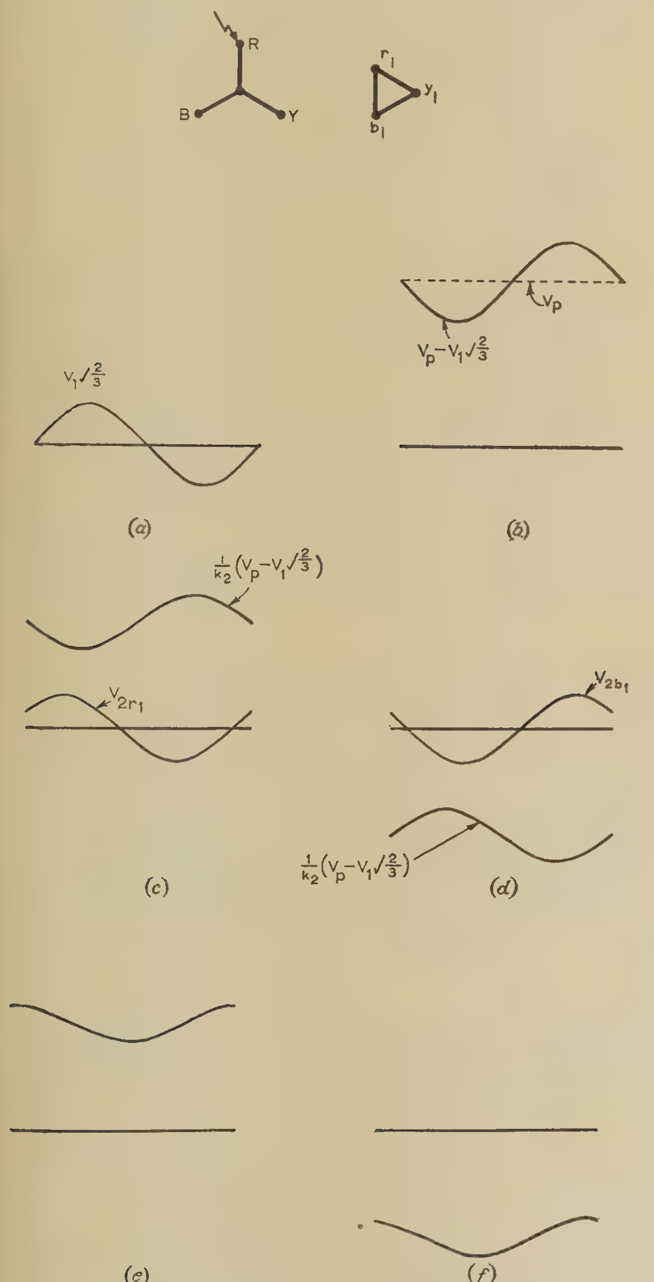

Fig. 10.—Voltages for single-phase impulse.

(*a*) Alternating voltage to earth, phase R.
(*b*) Impulse flashover voltage of protective-gap, phase R.
(*c*) Maximum surge voltage transmitted from h.v. winding, and phase voltage, phase r_1.
(*d*) Maximum surge voltage transmitted from h.v. winding, and phase voltage, phase b_1.
(*e*) Maximum voltage to earth at terminal r_1.
(*f*) Maximum voltage to earth at terminal b_1.

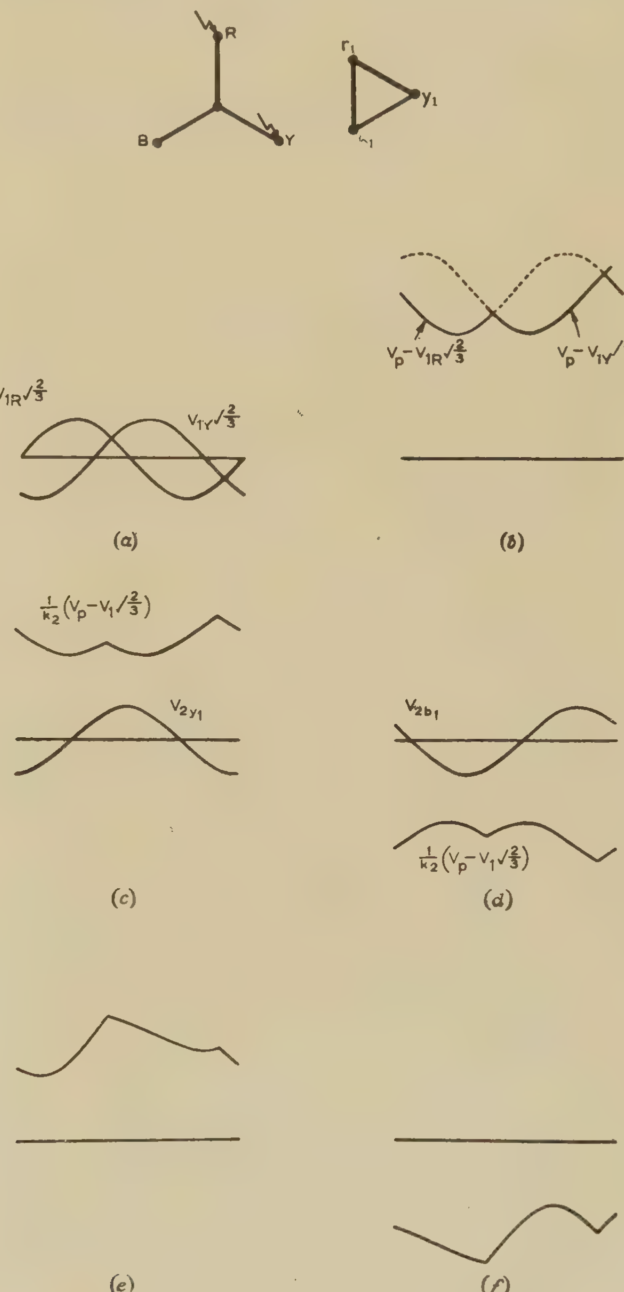

Fig. 11.—Voltages for 2-phase impulse.

(*a*) Alternating voltage to earth, phases R and Y.
(*b*) Impulse flashover voltages of protective gaps, phases R and Y.
(*c*) Maximum surge voltage transmitted to l.v. winding, and phase voltage, phase y_1.
(*d*) Maximum surge voltage transmitted to l.v. winding, and phase voltage, phase b_1.
(*e*) Maximum voltage to earth at terminal y_1.
(*f*) Maximum voltage to earth at terminal b_1.

discussed in Sections 4 and 5, a similar curve may be drawn of the maximum voltage $1/k_2[V_p - V_1\sqrt{\tfrac{2}{3}}]$ which may be transferred to the secondary terminals as shown in Figs. 10(*c*) and 10(*d*). These two diagrams also show the phases of the 50 c/s voltages at these terminals, V_{2r_1} and V_{2b_1}. Adding this to the maximum voltage which may be transferred gives the maximum voltage stress to earth which may occur at the l.v. terminal and thus the applied voltage which reaches the alternator terminals [see Figs. 10(*e*) and 10(*f*)].

Fig. 11 shows a similar construction for a 2-phase impulse, but here the maximum surge voltage which will not cause flash-over of the protective gap is the difference between the protective-gap setting and the h.v. winding phase voltage at either of two terminals. This causes the two discontinuities in the curve in Fig. 11(*b*).

A full mathematical analysis of this appears in Section 11.2, where it is shown that the maximum voltage which may appear at the alternator terminals is given by

$$\frac{1}{k_2}V_p + \sqrt{\left[\frac{2}{3}\left(\frac{1}{k_1^2} + \frac{1}{k_2^2} - \frac{\sqrt{3}}{k_1k_2}\right)\right]}V_1 \quad . \quad . \quad (11)$$

(7) VOLTAGE TRANSFERRED THROUGH A 132/11 kV TRANSFORMER

As an example, consider a 132 kV transformer with a protective gap having a flashover voltage of 550 kV. This corresponds roughly to transformer Y. Assume that 8·8% of the applied voltage is transferred to the l.v. terminals as in transformer Y, or $k_2 = 11{\cdot}36$. The transformer ratio, k_1, is 12. Substituting these values in eqn. (11) gives a possible voltage of 53·6 kV at the alternator terminals. This is about 1·65 times the normal test voltage of 23 kV r.m.s. for a machine of this voltage.

(8) CONCLUSIONS

The tests on transformers coupled to alternators indicate that the most important voltage transference through the transformer is due to coupling between the secondary winding and flux in the main core set up by the impulse current in the primary winding. This voltage may have an oscillatory or a dead-beat characteristic, depending on test conditions. In all experiments carried out the transferred voltage has been oscillatory with a dead-beat component.

Three methods are mentioned in the paper for estimating the maximum value of the transferred voltage, varying from a simple assumption that the 50 c/s transformation ratio (line-to-line voltages) is valid to more complex formulae involving the various circuit constants. Comparison of the results obtained does not indicate an accuracy much better than about ± 50% of the actual test value, although in most cases it is nearer ±25%. A high degree of accuracy cannot be expected, however, in view of the assumptions necessary to derive the formulae.

Voltage-distribution tests on an alternator connected to a transformer indicate that the transferred voltage is approximately linearly distributed, and thus there is little danger of interturn breakdowns occurring in the machine windings. These tests also show that the earthing of the alternator neutral point makes little difference to the alternator voltage distribution. This implies that protective circuits at the alternator neutral will also have no effect on the impulse voltage distribution.

A study of the effect of the power-frequency voltages on the surge voltages transferred through the transformer indicates that it may be necessary to add an additional 10% of the transferred voltage in a typical case to allow for the effect of the alternating voltages.

(9) ACKNOWLEDGMENTS

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(11) APPENDICES

(11.1) Approximate Solution for a Transformer connected to an Alternator

(11.1.1) Single-Phase Impulse.

Assume an equivalent circuit as shown in Fig. 2(*a*). From the symmetry of the circuit it will be seen that no voltage will occur across phase NY of the alternator, and therefore no current will flow and the presence of this link may be neglected.

Writing the impedance of the transformer phase RY in operational form and referring it to the l.v. winding gives

$$\frac{1}{k^2}(Z_2 + pL) \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Similarly, the effective impedance between terminals R and B may be written

$$\frac{1}{\dfrac{k^2}{2(Z_2 + pL)} + \dfrac{pC}{2} + \dfrac{1}{2Z_1}} \quad . \quad . \quad . \quad . \quad (13)$$

$$= \frac{2(pL + Z_2)}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + k^2} \quad . \quad . \quad (14)$$

The equivalent impedance of one phase will be half of this, namely

$$\frac{pL + Z_2}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + k^2} \quad . \quad . \quad (15)$$

The equivalent impedance of the inductance L of the impulsed phase referred to the l.v. terminal is pL/k^2.

In operational form the applied impulse $V\varepsilon^{-\alpha t}$ becomes (see Reference 9)

$$\frac{V}{p+\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Hence the voltage v across RN, i.e. that applied to an alternator phase, may be written

$$v = \frac{\dfrac{pL+Z_2}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + k^2}}{\dfrac{2(pL+Z_2)}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + k^2} + \dfrac{pL}{k^2}} \cdot \frac{V}{k(p+\alpha)} \quad . \quad (17)$$

$$= \frac{Vk(pL+Z_2)}{L^2C\left[p^3 + p^2\left(\dfrac{Z_2}{L} + \dfrac{1}{CZ_1}\right) + p\left(\dfrac{Z_2}{LCZ_1} + \dfrac{3k^2}{LC}\right) + \dfrac{2k^2Z_2}{L^2C}\right](p+\alpha)} \quad . \quad . \quad . \quad . \quad (18)$$

The cubic term in the denominator may have either three real factors or one real and two complex factors, as expressed in Section 4.

Considering first the real solutions, eqn. (18) may be written

$$v = \frac{Vk}{L^2C}\frac{pL+Z_2}{(p+\alpha)(p+\beta)(p+\gamma)(p+\Delta)} \quad . \quad . \quad (19)$$

The transform may now be inverted by the usual rules[9] to give the expression

$$v = \frac{Vk}{L^2C}\left[\frac{Z_2-\alpha L}{(\beta-\alpha)(\gamma-\alpha)(\Delta-\alpha)}\varepsilon^{-\alpha t} + \frac{Z_2-\beta L}{(\alpha-\beta)(\gamma-\beta)(\Delta-\beta)}\varepsilon^{-\beta t}\right.$$
$$\left. + \frac{Z_2-\gamma L}{(\alpha-\gamma)(\beta-\gamma)(\Delta-\gamma)}\varepsilon^{-\gamma t} + \frac{Z_2-\Delta L}{(\alpha-\Delta)(\beta-\Delta)(\gamma-\Delta)}\varepsilon^{-\Delta t}\right] \quad . \quad . \quad . \quad . \quad (20)$$

If, however, the roots of the cubic are complex, eqn. (18) must be written

$$v = \frac{Vk}{LC}\frac{pL+Z_2}{(p+\alpha)(p+\beta)[(p+\gamma)^2+\omega^2]} \quad . \quad . \quad (21)$$

Inverting the transform as shown in Section 11.1.3 gives

$$v = \frac{Vk}{L^2C}\left[\frac{1}{\beta-\alpha}\left\{\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2}\varepsilon^{-\alpha t} - \frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\varepsilon^{-\beta t}\right.\right.$$
$$\left. - \left[\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2} - \frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\right]\varepsilon^{-\gamma t}\cos\omega t\right\}$$
$$+ \frac{Z_2[\alpha\beta-\gamma(\alpha+\beta-\gamma)-\omega^2] - L[\alpha\beta\gamma-(\gamma^2+\omega^2)(\alpha+\beta-\gamma)]}{\omega[(\gamma-\alpha)^2+\omega^2][(\gamma-\beta)^2+\omega^2]}$$
$$\left.\times\, \varepsilon^{-\gamma t}\sin\omega t\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

(11.1.2) **2-Phase Impulse.**

Using the same notation as before and assuming the equivalent circuit as shown in Fig. 2(*b*), the points B and N can be seen to be at equal voltage by symmetry. Hence the voltages across RN and NY are equal.

The impedance across RY is given by

$$\frac{1}{\dfrac{pC}{2} + \dfrac{1}{2Z_1} + \dfrac{k^2}{Z_2+pL}} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

$$= \frac{2(pL+Z_2)}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + 2k^2} \quad . \quad . \quad (24)$$

As before, the voltage across RN ($= v$) may be written

$$v = \frac{\dfrac{pL+Z_2}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + 2k^2}}{\dfrac{pL+Z_2}{p^2LC + p\left(CZ_2 + \dfrac{L}{Z_1}\right) + \dfrac{Z_2}{Z_1} + 2k^2} + \dfrac{pL}{k^2}} \cdot \frac{V}{k(p+\alpha)} \quad (25)$$

$$= \frac{Vk}{L^2C}\frac{(pL+Z_2)}{\left[p^3 + p^2\left(\dfrac{Z_2}{L} + \dfrac{1}{Z_1LC}\right) + p\left(\dfrac{Z_2}{LCZ_1} + \dfrac{3k^2}{LC}\right) + \dfrac{Z_2k^2}{L^2C}\right]}$$
$$\times \frac{1}{p+\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

This may be factorized as in the single-phase case and a similar inverse transform evaluated. The constants β, γ, Δ, and ω, however, will have slightly different values.

(11.1.3) **Evaluation of the Inverse Transforms required for the Solution of eqn. (21).**

Equations have been derived for the transformer l.v. winding voltage containing a Laplace transformation of the form

$$\frac{pL+Z_2}{(p+\alpha)(p+\beta)[(p+\gamma)^2+\omega^2]} \quad . \quad . \quad . \quad (27)$$

Applying the usual rules[9] for the evaluation of inverse transforms gives the expression

$$\frac{Z_2-\alpha L}{(\beta-\alpha)[(\gamma-\alpha)^2+\omega^2]}\varepsilon^{-\alpha t} + \frac{Z_2-\beta L}{(\alpha-\beta)[(\gamma-\beta)^2+\omega^2]}\varepsilon^{-\beta t}$$
$$+ \frac{(-\gamma-j\omega)L+Z_2}{(\alpha-\gamma-j\omega)(\beta-\gamma-j\omega)(-2j\omega)}\varepsilon^{(-\gamma-j\omega)t}$$
$$+ \frac{(-\gamma+j\omega)L+Z_2}{(\alpha-\gamma+j\omega)(\beta-\gamma+j\omega)2j\omega}\varepsilon^{(-\gamma+j\omega)t} \quad . \quad (28)$$

This may be simplified by converting the last two fractions to a common denominator:

$$\frac{1}{\beta-\alpha}\left[\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2}\varepsilon^{-\alpha t} - \frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\varepsilon^{-\beta t}\right]$$
$$+ \frac{\{[(\gamma+j\omega)L-Z_2](\alpha-\gamma+j\omega)(\beta-\gamma+j\omega)\varepsilon^{-j\omega t} + [(-\gamma+j\omega)L+Z_2](\alpha-\gamma-j\omega)(\beta-\gamma-j\omega)\varepsilon^{j\omega t}\}}{[(\alpha-\gamma)^2+\omega^2][(\beta-\gamma)^2+\omega^2]}\varepsilon^{-\gamma t} \quad . \quad (29)$$

The last fraction may be further simplified:

$$\frac{\begin{array}{r}\{[(\gamma+j\omega)L-Z_2][\alpha\beta-\gamma(\alpha+\beta)+\gamma^2-\omega^2]+j\omega[(\alpha-2\gamma+\beta)]\varepsilon^{-j\omega t}\\ +[(-\gamma+j\omega)L+Z_2][\alpha\beta-\gamma(\alpha+\beta)+\gamma^2-\omega^2]-j\omega[(\alpha-2\gamma+\beta)]\varepsilon^{j\omega t}\}\varepsilon^{-\gamma t}\end{array}}{2j\omega[(\alpha-\gamma)^2+\omega^2][(\beta-\gamma)^2+\omega^2]} \quad . \quad (30)$$

$$\frac{\left[\frac{1}{\omega}\{Z_2[\alpha\beta-\gamma(\alpha+\beta)+\gamma^2-\omega^2]-L[\alpha\beta\gamma-\gamma^2(\alpha+\beta-\gamma)-\omega^2(\alpha+\beta-\gamma)]\}\sin\omega t+[L(\alpha\beta-\gamma^2-\omega^2)-Z_2(\alpha+\beta-2\gamma)]\cos\omega t\right]\varepsilon^{-\gamma t}}{[(\alpha-\gamma)^2+\omega^2][(\beta-\gamma)^2+\omega^2]} \quad . \; . \; . \; . \; . \quad (31)$$

The term in cos ωt may be further simplified as follows:

$$\frac{L(\alpha\beta-\gamma^2-\omega^2)-Z_2(\alpha+\beta-2\gamma)}{[(\alpha-\gamma)^2+\omega^2][(\beta-\gamma)^2+\omega^2]}\varepsilon^{-\gamma t}\cos\omega t \quad . \quad (32)$$

Multiplying and dividing this by $(\beta-\alpha)$ yields

$$\frac{1}{\beta-\alpha}\left[\frac{\alpha L-Z_2}{(\gamma-\alpha)^2+\omega^2}-\frac{\beta L-Z_2}{(\gamma-\beta)^2+\omega^2}\right]\varepsilon^{-\gamma t}\cos\omega t \quad (33)$$

Hence the transform may be written

$$\frac{1}{(\beta-\alpha)}\left\{\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2}\varepsilon^{-\alpha t}-\frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\varepsilon^{-\beta t}-\left[\frac{Z_2-\alpha L}{(\gamma-\alpha)^2+\omega^2}-\frac{Z_2-\beta L}{(\gamma-\beta)^2+\omega^2}\right]\varepsilon^{-\gamma t}\cos\omega t\right\}$$
$$+\frac{Z_2[\alpha\beta-\gamma(\alpha+\beta-\gamma)-\omega^2]+L[\alpha\beta\gamma-(\gamma^2+\omega^2)(\alpha+\beta-\gamma)]}{\omega[(\gamma-\alpha)^2+\omega^2][(\gamma-\beta)^2+\omega^2]}\varepsilon^{-\gamma t}\sin\omega t \quad . \quad (34)$$

(11.1.4) **Derivation of Alternator Equivalent Capacitance.**

Assume a uniform distribution of voltage through the winding from the neutral point (voltage zero) to the line terminal.

The voltage at any point x will be

$$\frac{l-x}{l}v \quad . \; . \; . \; . \; . \; . \; . \; . \quad (35)$$

The total stored energy in an element δx will be

$$\frac{1}{2}\frac{C_g}{l}\left(\frac{l-x}{l}\right)^2 v^2\delta x \quad . \; . \; . \; . \; . \; . \quad (36)$$

The total energy stored in the winding is

$$\frac{1}{2}\frac{C_g}{l}\int_0^l\left(\frac{l-x}{l}\right)^2 v^2 dx=\frac{1}{6}C_g v^2 \quad . \; . \; . \quad (37)$$

which, when compared with the usual formula for the energy stored in a condenser charged to a voltage v, shows that the equivalent capacitance of the alternator winding is one-third of its actual capacitance to earth.

(11.2) **Derivation of the Maximum Amplitudes of Surges Transmitted through Star-Delta Transformers**

(11.2.1) **Single-Phase Surge.**

Use the same notation as before and consider the circuit shown in Figs. 12(a) and 12(b), with its accompanying vector diagram.

The alternating voltage on phase R will be $\frac{V_1\sqrt{2}}{\sqrt{3}}\sin\omega t$.

The maximum surge voltage which may occur on phase R without causing the protective gap to operate will be

$$V_p-\frac{V_1\sqrt{2}}{\sqrt{3}}\sin\omega t \quad . \; . \; . \; . \; . \; . \quad (38)$$

The surge voltage transferred to the l.v. winding will be

$$\frac{1}{k_2}\left(V_p-V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t\right) \quad . \; . \; . \; . \quad (39)$$

This will be positive on phase r_1 and negative on phase b_1, and will therefore be written

$$\pm\frac{1}{k_2}\left(V_p-V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t\right) \quad . \; . \; . \; . \quad (40)$$

Similarly the alternating voltage on the l.v. terminals, phases r_1 and b_1, may be written

$$\pm\frac{V_1}{k_1}\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t\pm\frac{\pi}{6}\right) \quad . \; . \; . \; . \quad (41)$$

Hence the total voltage at these terminals will be

$$\pm\left[\frac{1}{k_2}\left(V_p-V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t\right)+\frac{V_1}{k_1}\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t\pm\frac{\pi}{6}\right)\right] \quad (42)$$

or

$$\pm\left\{\frac{1}{k_2}V_p+V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\sin\left(\omega t\pm\frac{\pi}{6}\right)-\frac{1}{k_2}\sin\omega t\right]\right\} \quad (43)$$

$$=\pm\left\{\frac{1}{k_2}V_p+V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\left(\frac{\sqrt{3}}{2k_1}-\frac{1}{k_2}\right)\sin\omega t\pm\frac{1}{2k_1}\cos\omega t\right]\right\} \quad (44)$$

The maximum value of this expression is

$$\frac{1}{k_2}V_p+\sqrt{\left[\frac{2}{3}\left(\frac{1}{k_1^2}+\frac{1}{k_2^2}-\frac{\sqrt{3}}{k_1k_2}\right)\right]}V_1 \quad . \; . \quad (45)$$

If the phase displacement between the star and delta terminals had been reversed, as shown in Figs. 12(a) and 12(c), eqn. (42) would have been

$$\pm\left[\frac{1}{k_2}\left(V_p-V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t\right)+\frac{V_1}{k_1}\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t\mp\frac{\pi}{6}\right)\right] \quad (46)$$

which would have given the same value for eqn. (45).

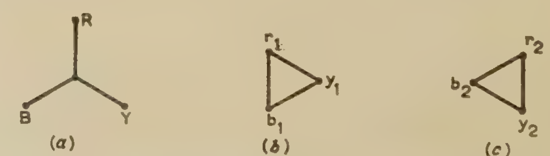

Fig. 12.—Vector diagrams for a star-delta transformer.
(a) H.V. winding.
(b) and (c) Alternative l.v. delta connections.

(11.2.2) **2-Phase Surges.**

Refer to the vector diagrams in Fig. 12 and consider a surge on phases R and Y. The 50 c/s h.v. terminal voltages must then be written

$$\text{Phase R:}\quad V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

$$\text{Phase Y:}\quad V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t-\frac{2\pi}{3}\right) \quad . \quad . \quad . \quad (48)$$

The maximum surge voltage which may appear on either line without causing the protective gap to operate would be

$$V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t \qquad \text{for } -\frac{\pi}{6}<\omega t<\frac{5\pi}{6} \quad . \quad (49)$$

$$V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t-\frac{2\pi}{3}\right) \text{ for } \frac{5\pi}{6}<\omega t<\frac{11\pi}{6} \quad . \quad (50)$$

If a protective gap operates, the surge on that phase is then removed so far as any transferred voltage is concerned. The conditions would then become similar to the single-phase impulse, except that the loading on the h.v. terminal which had flashed over would be greater than with a single-phase impulse. However, on the assumption that no flashovers occur, the surge voltages appearing at the l.v. terminals y_1 and b_1 or r_2 and b_2, depending on the mode of connection, would be

$$\pm\frac{1}{k_2}\left(V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t\right) \qquad \text{for } -\frac{\pi}{6}<\omega t<\frac{5\pi}{6} \quad (51)$$

$$\pm\frac{1}{k_2}\left[V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t-\frac{2\pi}{3}\right)\right] \text{ for } \frac{5\pi}{6}<\omega t<\frac{11\pi}{6} \quad (52)$$

From the vector diagram the alternating voltages at the various terminals may be derived and added to the surge voltages as follows:

Terminal y_1:

$$\frac{V_1}{k_1}\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t-\frac{\pi}{2}\right)+\frac{1}{k_2}\left(V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\omega t\right)$$

$$\text{for } -\frac{\pi}{6}<\omega t<\frac{5\pi}{6} \quad . \quad (53)$$

$$=\frac{1}{k_2}V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\left(\frac{1}{k_1}\cos\omega t+\frac{1}{k_2}\sin\omega t\right) \quad . \quad (54)$$

and

$$\frac{V_1}{k_1}\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t-\frac{\pi}{2}\right)+\frac{1}{k_2}\left[V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\sin\left(\omega t-\frac{2\pi}{3}\right)\right]$$

$$\text{for } \frac{5\pi}{6}<\omega t<\frac{11\pi}{6} \quad . \quad (55)$$

$$=\frac{1}{k_2}V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\cos\omega t+\frac{1}{k_2}\sin\left(\omega t-\frac{2\pi}{3}\right)\right] \quad (56)$$

Terminal b_1:

$$-\left\{\frac{1}{k_2}V_p + V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\sin\left(\omega t-\frac{\pi}{6}\right)-\frac{1}{k_2}\sin\omega t\right]\right\}$$

$$\text{for } -\frac{\pi}{6}<\omega t<\frac{5\pi}{6} \quad . \quad (57)$$

and

$$-\left\{\frac{1}{k_2}V_p + V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\sin\left(\omega t-\frac{\pi}{6}\right)-\frac{1}{k_2}\sin\left(\omega t-\frac{2\pi}{3}\right)\right]\right\}$$

$$\text{for } \frac{5\pi}{6}<\omega t<\frac{11\pi}{6} \quad . \quad (58)$$

Terminal r_2:

$$\frac{1}{k_2}V_p + V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\sin\left(\omega t-\frac{\pi}{6}\right)-\frac{1}{k_2}\sin\omega t\right]$$

$$\text{for } -\frac{\pi}{6}<\omega t<\frac{5\pi}{6} \quad . \quad (59)$$

and

$$\frac{1}{k_2}V_p + V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\sin\left(\omega t-\frac{\pi}{6}\right)-\frac{1}{k_2}\sin\left(\omega t-\frac{2\pi}{3}\right)\right]$$

$$\text{for } \frac{5\pi}{6}<\omega t<\frac{11\pi}{6} \quad . \quad (60)$$

Terminal b_2:

$$-\left[\frac{1}{k_2}V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\left(\frac{1}{k_1}\cos\omega t+\frac{1}{k_2}\sin\omega t\right)\right]$$

$$\text{for } -\frac{\pi}{6}<\omega t<\frac{5\pi}{6} \quad . \quad (61)$$

and

$$-\left\{\frac{1}{k_2}V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\cos\omega t+\frac{1}{k_2}\sin\left(\omega t-\frac{2\pi}{3}\right)\right]\right\}$$

$$\text{for } -\frac{5\pi}{6}<\omega t<\frac{11\pi}{6} \quad . \quad (62)$$

It will be noted that the voltages for the two modes of connection are identical, i.e. y_1 and b_2 and b_1 and r_2. It is therefore necessary to evaluate only one set of results to determine the maximum voltage which may occur.

Commencing with eqn. (54), by inspection it will be seen that this reaches a minimum value within the effective range and therefore cannot provide the maximum terminal voltage. Eqn. (56) may be expanded as follows:

$$\frac{1}{k_2}V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\frac{1}{k_1}\cos\omega t+\frac{1}{k_2}\left(-\frac{1}{2}\sin\omega t-\frac{\sqrt{3}}{2}\cos\omega t\right)\right] \quad . \quad . \quad . \quad . \quad (63)$$

$$=\frac{1}{k_2}V_p - V_1\frac{\sqrt{2}}{\sqrt{3}}\left[\left(\frac{1}{k_1}-\frac{\sqrt{3}}{2k_2}\right)\cos\omega t-\frac{1}{2k_2}\sin\omega t\right] \quad (64)$$

$$=\frac{1}{k_2}V_p + V_1\sqrt{\left[\frac{2}{3}\left(\frac{1}{k_1^2}+\frac{1}{k_2^2}-\frac{\sqrt{3}}{k_1k_2}\right)\right]}\sin(\omega t-\theta_1) \quad (65)$$

where

$$\left.\begin{aligned}\theta_1 &= \arc\sin\frac{\dfrac{1}{k_1}-\dfrac{\sqrt{3}}{2k_2}}{\sqrt{\left(\dfrac{1}{k_1^2}+\dfrac{1}{k_2^2}-\dfrac{\sqrt{3}}{k_1k_2}\right)}}\\ &= \arc\sin\frac{2k_2-k_1\sqrt{3}}{\sqrt{(4k_2^2+4k_1^2-4k_1k_2\sqrt{3})}}\\ &= \arc\cos\frac{\dfrac{1}{2k_2}}{\sqrt{\left(\dfrac{1}{k_1^2}+\dfrac{1}{k_2^2}-\dfrac{\sqrt{3}}{k_1k_2}\right)}}\\ &= \arc\cos\frac{k_1}{\sqrt{(4k_2^2+4k_1^2-4k_1k_2\sqrt{3})}}\end{aligned}\right\} \quad (66)$$

For eqn. (65) to be a maximum

$$\left.\begin{aligned} \omega t - \theta_1 &= \frac{\pi}{2} \\ \text{or} \qquad \theta_1 &= \omega t - \frac{\pi}{2} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (67)$$

The limiting values of θ are given by $k_1 = 0$ and $k_2 = 0$, since they cannot be negative.

At

$$\left.\begin{aligned} k_1 &= 0 \quad \cos\theta_1 = \frac{1}{2} \quad \sin\theta_1 = -\frac{\sqrt{3}}{2} \quad \theta_1 = -\frac{\pi}{3} \\ k_2 &= 0 \quad \cos\theta_1 = 0 \quad \sin\theta_1 = 1 \quad \theta_1 = \frac{\pi}{2} \end{aligned}\right\} \quad (68)$$

Hence maxima will occur between $\omega t = \pi/6$ and $\omega t = \pi$. The equation is valid only for $5\pi/6 < \omega t < 11\pi/6$.

At the beginning of this period, i.e. $\omega t = 5\pi/6$, maximum voltage will occur with

$$\theta_1 = \frac{5\pi}{6} - \frac{\pi}{2} = \frac{\pi}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

Substituting this in eqn. (66) for $\cos\theta_1$ gives

$$\frac{1}{2} = \frac{\dfrac{1}{2k_2}}{\sqrt{\left(\dfrac{1}{k_1^2} + \dfrac{1}{k_2^2} - \dfrac{\sqrt{3}}{k_1k_2}\right)}} \quad . \quad . \quad . \quad . \quad (70)$$

or

$$k_2 = k_1\sqrt{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

Hence between the limits $k_2 = 0$ and $k_2 = k_1\sqrt{3}$ the l.v. terminal voltage may reach its maximum amplitude of

$$\frac{1}{k_2}V_p + V_1\sqrt{\left[\frac{2}{3}\left(\frac{1}{k_1^2} + \frac{1}{k_2^2} - \frac{\sqrt{3}}{k_1k_2}\right)\right]} \quad . \quad . \quad (72)$$

and for $k_2 > k_1\sqrt{3}$ the maximum voltage will be given by

$$\frac{1}{k_2}V_p + V_1\sqrt{\left[\frac{2}{3}\left(\frac{1}{k_1^2} + \frac{1}{k_2^2} - \frac{\sqrt{3}}{k_1k_2}\right)\right]}\sin\left(\frac{5\pi}{6} - \theta_1\right)\Bigg] \quad (73)$$

Expanding the last term and substituting eqn. (66),

$$\sin\left(\frac{5\pi}{6} - \theta_1\right) = \frac{1}{2}\cos\theta_1 + \frac{\sqrt{3}}{2}\sin\theta_1 \quad . \quad . \quad (74)$$

$$= \frac{1}{4\sqrt{(k_1^2 + k_2^2 - k_1k_2\sqrt{3})}}[k_1 + \sqrt{3}(2k_2 - k_1\sqrt{3})] \quad (75)$$

$$= \frac{k_2\sqrt{3} - k_1}{2\sqrt{(k_1^2 + k_2^2 - k_1k_2\sqrt{3})}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (76)$$

Substituting this in eqn. (73) gives the maximum voltage as

$$\frac{1}{k_2}V_p + V_1\left(\frac{1}{k_1} - \frac{1}{k_2\sqrt{3}}\right)\frac{1}{\sqrt{2}} \quad . \quad . \quad . \quad (77)$$

A similar argument may be applied to the expressions for th voltage at terminal b_1. Eqn. (57) may be shown to have maximum of

$$\frac{1}{k_2}V_p - V_1\sqrt{\left[\frac{2}{3}\left(\frac{1}{k_1^2} + \frac{1}{k_2^2} - \frac{\sqrt{3}}{k_1k_2}\right)\right]} \quad . \quad . \quad (78)$$

for $0 < k_2 < k_1\sqrt{3}$; but for $k_2 > k_1\sqrt{3}$ the maximum become

$$\frac{1}{k_2}V_p + V_1\left(\frac{1}{k_1} - \frac{1}{k_2\sqrt{3}}\right)\frac{1}{\sqrt{2}} \quad . \quad . \quad . \quad (79)$$

Eqn. (58) can be shown to be like eqn. (54) and to have i maximum outside its range of validity.

[The discussion on the above paper will be found on page 370.]

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THE PROPAGATION OF SURGE VOLTAGES THROUGH TURBO-ALTERNATORS WITH CONCENTRIC-CONDUCTOR-TYPE WINDINGS

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SUMMARY

The study of the propagation of surge voltages in conventional types of alternator winding is modified to be applicable to the concentric-conductor type of winding used for some machines having a terminal voltage of 22 or 33 kV. The theoretical analysis shows that the wave entering the winding at the machine terminal sets up series of travelling waves between each pair of adjacent conductors in the bars. The travelling waves have different velocities, which are characteristic of the conductors. The waves in the outer conductor travel slowest, owing to the presence of the iron core which forms the return circuit. The waves are reflected and refracted at the junction of the various sections of the winding.

Test results on a typical machine are given, and the initial voltage distribution is explained in terms of the theoretical travelling waves. Measured values for the winding surge impedance are compared with those deduced theoretically from the various circuit parameters.

LIST OF PRINCIPAL SYMBOLS

C_1 = Capacitance per unit length of conductor between bull and inner conductors.
C_2 = Capacitance per unit length of conductor between inner and outer conductors.
C_3 = Capacitance per unit length of conductor between outer conductor and earth.
C_t = Capacitance per unit length between adjacent conductors of the same section of the winding.
I_1 = Current in bull conductors.
I_2 = Current in inner conductors.
I_3 = Current in outer conductors.
I_{A1}, I'_{B1} = Currents corresponding to voltages v_{A12}, v'_{B12}, etc. (see Section 9.4).
$K = C_t l^2 \omega^2$.
l = Length of a turn in the winding.
L_1, L_2, L_3 = Self-inductance of bull, inner, and outer conductors.
M_{12}, M_{13}, M_{23} = Mutual inductances between bull, inner, and outer conductors.
u = Velocity of propagation.
u_a, u_b, u_c = Velocity of propagation of low-frequency components of travelling waves, V_a, V_b, V_c.
v_1 = Voltage between bull conductors and earth.
v_2 = Voltage between inner conductors and earth.
v_3 = Voltage between outer conductors and earth.
v_{12} = Voltage between bull and inner conductors.
v_{23} = Voltage between inner and outer conductors.
v_{A12}, v_{B12}, etc. = Voltage between bull and inner conductors, etc., when voltage is applied to the phase terminal (see Section 9.4).
V_1, V_2, V_3 = Voltage amplitude of travelling-wave components of frequency ω in the windings.
V_a, V_b, V_c = Voltage amplitude of travelling wave components of low frequency travelling with velocities u_a, u_b and u_c.
V_{line} = Voltage amplitude at terminal of incoming travelling waves.
x = Distance along conductors from the terminal.
Z_{12} = Limiting surge impedance of bull conductors.
Z_{23} = Limiting surge impedance of inner conductors.
Z_{30} = Limiting surge impedance of outer conductors.
Z_w = Limiting surge impedance of alternator winding.

Dr. Robinson is with C. A. Parsons and Co., Ltd.

(1) INTRODUCTION

Previous papers[1,2] have dealt with the theory of the propagation of surge voltages through large alternators with uniformly-insulated conventional-type windings, and the present paper extends the work to cover alternator windings with concentric-type conductors. The published information on the propagation of surge voltages through this type of alternator is very scanty and is almost entirely confined to a paper by Friedlander[3] and the subsequent discussion; that paper is a pure mathematical analysis, because unfortunately the only test data the author had available were on a length of concentric-conductor cable. Some test data on actual machines are given in the various contributions to the subsequent discussion.

(2) GENERAL CONSTRUCTION OF MACHINE WINDING AND DERIVATION OF THE EQUIVALENT CIRCUIT

The concentric type of conductor[4,5] is used in some alternators generating at voltages of 22 and 33 kV; the winding of each phase is divided into two or three sections, each of which generates a (phase) voltage of about 6·4 kV corresponding to one-half or one-third of the total machine voltage. The slot conductors are round and contain two or three circular concentric conductors, one belonging to each section of the winding. The end-connections of the bars are made from round copper bar.

The advantage of this type of winding is that under normal working conditions the insulation of each conductor is stressed only to a fraction of the total machine voltage, thus enabling a more economic design to be used. The insulation between the outer conductor of each bar and the core is made thicker than the remainder of the insulation, to guard against abnormal voltages which occur under fault conditions.

It is proposed here to deal only with the 3-core concentric-conductor machine giving a line voltage of 33 kV, which is more common than the 2-core machine working at 22 kV, although the theory and test behaviour of both types are similar.

The three sections of each conductor bar, commencing at the centre, are usually referred to as the bull, the inner, and the outer conductors. It will be appreciated that each coil of the winding possesses the electrical parameters C_1, C_2, C_3 and C_t (assumed to be equal for all sections of the winding), L_1, L_2 and L_3, M_{12}, M_{23} and M_{13}, as defined in the List of Principal Symbols.

The equivalent circuit may be represented by the network shown in Fig. 1. In order to express the characteristics of the winding in the form of differential equations involving the

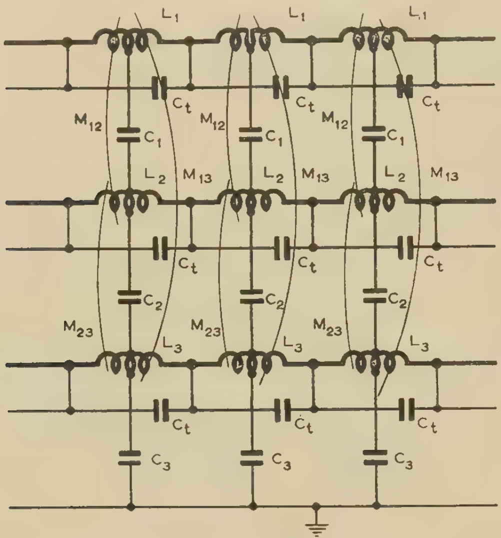

Fig. 1.—Equivalent circuit for a 3-core concentric-conductor alternator winding.

distributed circuit constants, it is necessary to assume that each section of the winding is uniform instead of consisting of alternate lengths of conductor bar and end-winding.

(2.1) Equations for Travelling Waves in the Winding

If l is the length of a turn in the winding consisting of two conductor bars and their associated end-windings, the fundamental equations for the voltages to earth and the currents in the bull, inner and outer conductors may be written as follows:

For the bull conductors:

$$-\frac{\partial I_1}{\partial x} = C_1\left(\frac{\partial v_1}{\partial t} - \frac{\partial v_2}{\partial t}\right) - C_t l^2 \frac{\partial^3 v_1}{\partial x^2 \partial t} \quad . \quad . \quad . \quad (1)$$

$$-\frac{\partial v_1}{\partial x} = L_1\frac{\partial I_1}{\partial t} + M_{12}\frac{\partial I_2}{\partial t} + M_{13}\frac{\partial I_3}{\partial t} \quad . \quad . \quad . \quad (2)$$

For the inner conductors:

$$-\frac{\partial I_2}{\partial x} = C_2\left(\frac{\partial v_2}{\partial t} - \frac{\partial v_3}{\partial t}\right) - C_1\left(\frac{\partial v_1}{\partial t} - \frac{\partial v_2}{\partial t}\right) - C_t l^2 \frac{\partial^3 v_2}{\partial x^2 \partial t} \quad . \quad (3)$$

$$-\frac{\partial v_2}{\partial x} = M_{12}\frac{\partial I_1}{\partial t} + L_2\frac{\partial I_2}{\partial t} + M_{13}\frac{\partial I_3}{\partial t} \quad . \quad . \quad . \quad (4)$$

For the outer conductors:

$$-\frac{\partial I_3}{\partial x} = C_3\frac{\partial v_3}{\partial t} - C_2\left(\frac{\partial v_2}{\partial t} - \frac{\partial v_3}{\partial t}\right) - C_t l^2 \frac{\partial^3 v_3}{\partial x^2 \partial t} \quad . \quad (5)$$

$$-\frac{\partial v_3}{\partial x} = M_{13}\frac{\partial I_1}{\partial t} + M_{23}\frac{\partial I_2}{\partial t} + L_3\frac{\partial I_3}{\partial t} \quad . \quad . \quad . \quad (6)$$

These equations are not soluble in the general form, but approximate solutions which indicate the form of result to be anticipated may be obtained by introducing various simplifications. It is well known that a high-frequency magnetic field cannot exist inside the conductor carrying the current. Consider a current flowing in the outer conductor: the effective magnetic field which it causes will all be outside the conductor; the same field will therefore link all the conductors in the bar and thus th following approximation may be written:

$$\left.\begin{aligned} M_{13} \simeq M_{23} \simeq L_3 \\ \text{Similarly} \qquad M_{12} \simeq L_2 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad ($$

Further evidence for making this assumption is provided b the fact that tests on a conventionally wound machine[1] showe that the mutual inductance between the two conductors in a sl was very nearly equal to the self-inductance of one of the co ductors. This approximation will be more nearly correct in th concentric conductor machine.

As shown in the above paper and its discussion,[1] the applie impulse wave may be resolved into sinusoidal components b Fourier's theorem, the magnitudes of these components bein approximately inversely proportional to their frequency. It therefore possible as a further approximation to consider on the low-frequency components (i.e. let ω tend to zero). As show in Section 9.1, this eliminates the terms in C_t, and the resultan equations show that waves of these component frequencies trav in the winding with three velocities, namely

$$u_a^2 = \frac{1}{(L_1 - L_2)C_1} \quad . \quad . \quad . \quad . \quad . \quad .$$

$$u_b^2 = \frac{1}{(L_2 - L_3)C_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad ($$

$$u_c^2 = \frac{1}{L_3 C_3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1$$

If the terms in C_t had not been eliminated these equatio would have had a term in ω showing that the velocities we functions of frequency.

Substituting these velocities in the original equations giv the solutions

$$v_1 = V_a \varepsilon^{j\omega\left(t - \frac{x}{u_a}\right)} + V_b \varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} + V_c \varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad . \quad (1$$

$$v_2 = V_b \varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} + V_c \varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad . \quad . \quad . \quad . \quad . \quad (1$$

$$v_3 = V_c \varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1$$

Similar solutions exist for waves travelling in the rever direction, as is shown by the existence of negative values for th velocities. Subtraction of the values of v_1, v_2 and v_3 shows th the wave component V_a represents a voltage stress in the bul inner insulation, and V_b a voltage stress in the inner–out insulation. It will thus be seen that the travelling waves in th machine are best considered as waves travelling along each tub i.e. between adjacent conductors. The velocities of propagatio will also be seen to be peculiar to the particular tubes.

(2.2) Surge Impedances of Sections of the Winding

If the surge impedances of the three sections of the windi are defined as

$$Z_{12} = \sqrt{\left(\frac{L_1 - L_2}{C_1}\right)} \quad . \quad . \quad . \quad . \quad . \quad (1$$

$$Z_{23} = \sqrt{\left(\frac{L_2 - L_3}{C_2}\right)} \quad . \quad . \quad . \quad . \quad . \quad (1$$

$$Z_3 = \sqrt{\left(\frac{L_3}{C_3}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1$$

it is shown in Section 9.3 that the equations for the propagati

of the surge voltages between sections of the winding can be written as

$$v_{12} = v_1 - v_2 = Z_{12}I_1 \quad . \quad . \quad . \quad . \quad (17)$$

$$v_{23} = v_2 - v_3 = Z_{23}(I_1 + I_2) \quad . \quad . \quad . \quad . \quad (18)$$

$$v_3 = Z_3(I_1 + I_2 + I_3) \quad . \quad . \quad . \quad . \quad (19)$$

(2.3) Initial Voltage Distribution

From the above equations and the conditions imposed by the connections between sections it can be shown that a surge V_{line} entering the winding at the phase terminal sets up waves in all three conductors which travel away from the connecting links in both directions. The magnitudes of these component waves are given by the following equations:

For the bull conductor wave at the terminal,

$$v_{A12} = \frac{V_{line}}{1 + \dfrac{Z_{23}}{Z_{12} + Z_{23}} + \dfrac{Z_3}{Z_{12}}\left[1 + \dfrac{Z_3(Z_3 + Z_n)}{Z_3Z_n + (Z_{23} + Z_3)(Z_3 + Z_n)}\right]} \quad . \quad . \quad . \quad . \quad (20)$$

For the bull conductor wave and the inner-conductor wave at the bull–inner link,

$$v_{B12} = v_{B23} = \frac{Z_{23}}{Z_n + Z_{23}}v_{A12} \quad . \quad . \quad . \quad . \quad (21)$$

For the inner-conductor wave and the outer-conductor wave at the inner–outer link,

$$v_{C23} = v_{C3} = \frac{Z_3}{Z_{12}}\left[1 - \frac{Z_3(Z_3 + Z_n)}{Z_3Z_n + (Z_{23} + Z_3)(Z_3 + Z_n)}\right]v_{A12} \quad . \quad (22)$$

For the waves at the neutral,

$$v_{DN} = \frac{v_{C3}}{1 + Z_{23}\left(\dfrac{Z_3 + Z_n}{Z_3Z_n}\right)} \quad . \quad . \quad . \quad . \quad (23)$$

where Z_n is the impedance to earth at the neutral as formed by the other phases in parallel with the star-point earthing resistor if used.

(2.4) Winding Surge Impedance

The surge impedance of the winding for the low-frequency components of the incoming wave may be derived from eqn. (17), since it is the ratio I_1/V_{line}:

$$Z_w = \frac{V_{line}}{I_1} = Z_{12}\frac{V_{line}}{v_{12}} \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Substituting from eqn. (20) gives

$$Z_w = Z_{12} + \frac{Z_{12}Z_{23}}{Z_{12} + Z_{23}} + Z_3 - \frac{Z_3^2}{Z_{23} + Z_3 + \dfrac{Z_3Z_n}{Z_3 + Z_n}} \quad . \quad (25)$$

(2.5) Reflections at Links between Sections of the Winding

As already explained, the incoming surge at the terminal sets up voltages at the links between the various sections of the winding. These voltages travel along the windings and eventually reach the next link. Owing to the different characteristics of the winding in each section the waves are reflected and refracted on arrival at the links. An analysis of the reflections which occur at the various links for waves travelling towards the neutral is given in Section 9.6, which shows that a wave arriving at a link is not merely split into two sections, one of which is reflected backwards and the other of which continues through the link, but, in addition, voltages are induced in the other conductors. Since all the waves will arrive at the links at slightly different instants, owing to the different velocities of propagation of waves in the various sections of the winding, it will be realized that a very complex system of travelling waves will be set up after the first few microseconds. Similar results may be expected to occur for the reflection of waves travelling towards the line terminal.

(2.6) Critical Frequency

If, when considering the general equation for the propagation of the voltage through the winding, the velocity is equated to zero instead of the frequency, the values of ω obtained will give the critical frequency (see Section 9.2). The resulting equation is a cubic in ω^2 and can be solved only in particular cases. No theoretical treatment of the behaviour of the component frequencies above the critical frequencies is given, as the experimental results show that these frequencies do not enter the winding with any measurable amplitude, owing to the large effective capacitance of the windings at these frequencies. They cannot therefore affect the voltage distribution, and any treatment of their distribution would be academic.

(3) TESTS ON A CONCENTRIC-CONDUCTOR ALTERNATOR

An opportunity to compare the theoretical deductions with test results occurred when recurrent-surge tests were carried out on a 3-core concentric-conductor machine, the general particulars of which were as follows:

Machine E.—A 2-pole 3-phase 30 MW 33-kV alternator with 32 conductor bars per phase. The inner and outer conductors were fully wound, but only 28 bull conductors were wound. The bull conductors in the four bars nearest the phase terminal were left unwound, giving 92 conductors per phase.

A relatively large impulse-generator capacitance of 1 μF was found to be essential for these tests, owing to the low impedance of the test object. This gave an impulse voltage rising to between 55 and 80% of its peak value in 1 microsec followed by a slow rise in about 10 microsec to the crest. The wavetail duration was approximately 50 microsec throughout.

Tests were carried out to determine the voltage distribution in the windings with the neutral point earthed and isolated, and with the impulse applied to one, two and three phases. With the capacitance-tapping technique[6] it was possible to take oscillograms of the voltage to earth at a large number of points along one phase. Then, by applying the impulse to the various terminals and assuming that all three phases were identical, it was possible to obtain the distribution throughout the machine. With two cathode-follower units and by suitable choice of the tapping points it was possible to measure the voltages between the different sections of the winding and thus to obtain the voltages across the conductor insulation. In all the tests those phases not connected to the impulse generator were earthed through 500-ohm resistors to simulate transmission lines.

Impulse-voltage distribution curves are given for various test conditions in Figs. 2–5. Only the impulsed phases are shown for the single-phase condition, since the voltages in the other two phases are relatively small. This is well illustrated by the 2-phase neutral-isolated curves in Fig. 4, where the voltages to earth in two phases are given.

(4) EVALUATION OF CIRCUIT CONSTANTS

The evaluation of the circuit constants can be carried out in a concentric-conductor machine only if the assumptions that the

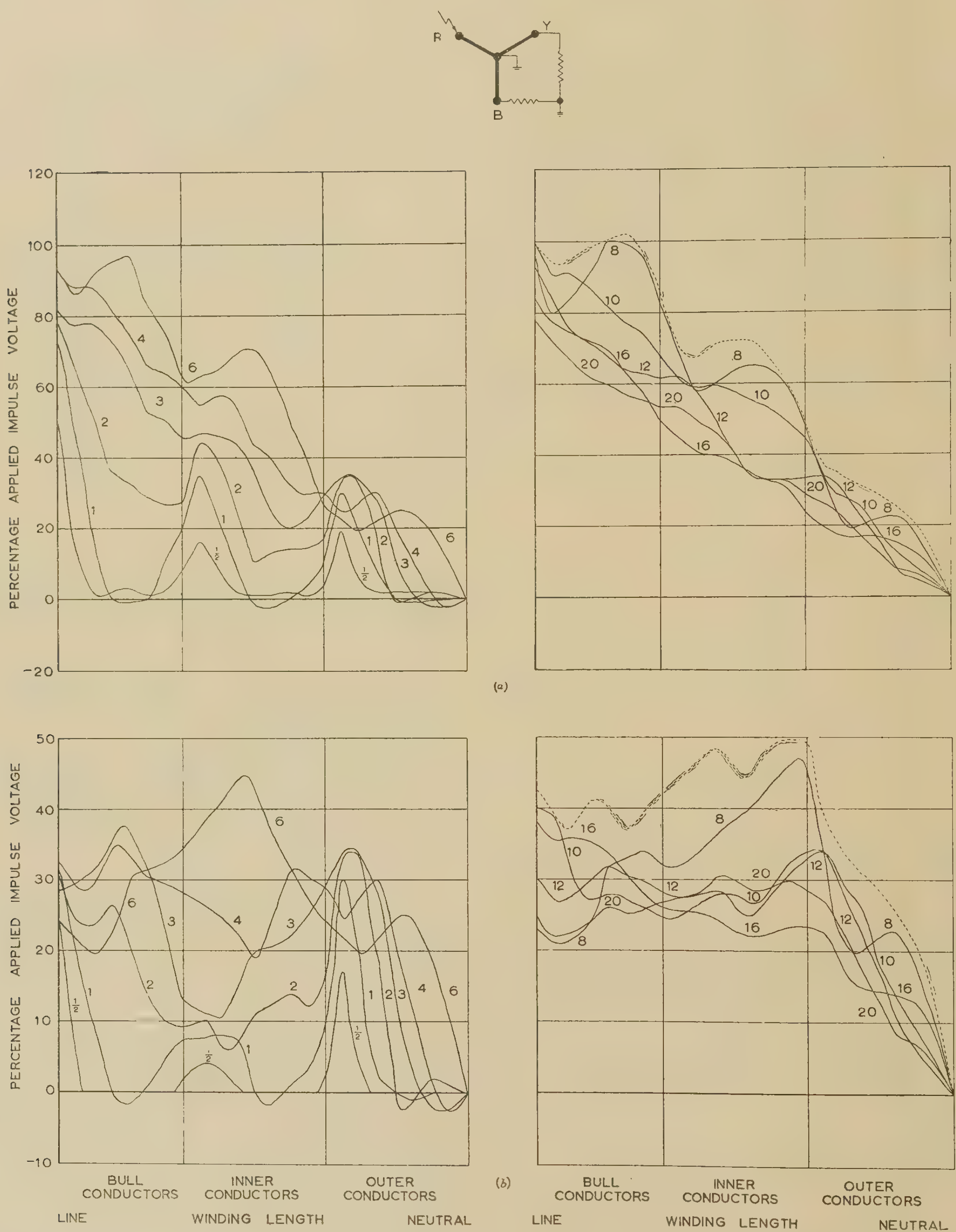

Fig. 2.—Impulse-voltage distribution in machine E, phase R; impulse applied to phase R, neutral point earthed.

(*a*) Voltages to earth.
(*b*) Voltages between conductors.
Figures on curves are times in microseconds.
Broken lines show maximum voltages.
Vertical lines indicate positions of links.

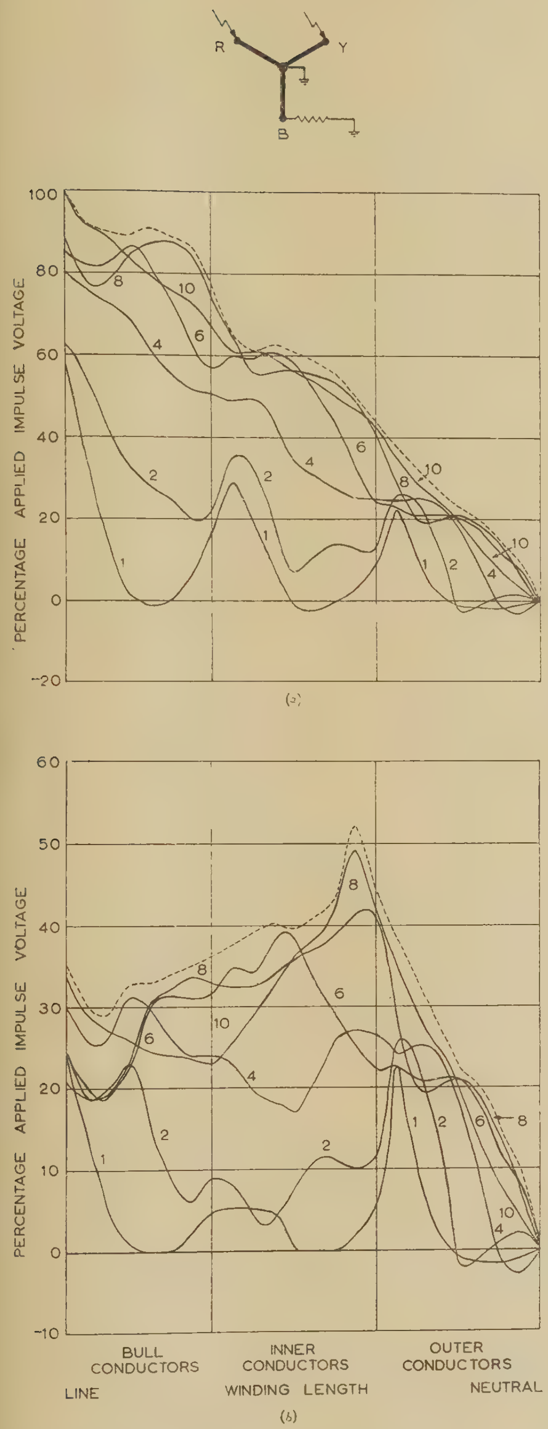

Fig. 3.—Impulse-voltage distribution in machine E, phase R; impulse applied to phases R and Y, neutral point earthed.

(*a*) Voltage to earth.
(*b*) Voltage between conductors.
Figures on curves are times in microseconds.
Broken lines show maximum voltages.
Vertical lines indicate positions of links.

mutual inductances are equal to the self-inductances (as explained in Section 2.1) are valid. It is then possible to obtain expressions for the wave velocities and hence, with a knowledge of the capacitances, to calculate the inductances.

(4.1) Winding Capacitances

On a concentric-conductor machine the winding capacitances must be measured before the links between the various sections of the winding are inserted. In the machine as used for the tests these capacitances were as follow:

Bull conductor to inner conductor: $C_1 = 2\,536\ \mu\mu$F per bar.
Inner conductor to outer conductor: $C_2 = 3\,000\ \mu\mu$F per bar.
Outer conductor to earth (core): $C_3 = 2\,071\ \mu\mu$F per bar.

(4.2) Winding Inductances

The tests show that the approximate velocities of propagation of wave in the stator winding tested are

Bull–inner conductors: 11 bars/microsec.
Inner–outer conductors: 16 bars/microsec.
Outer conductors: 3·4 bars/microsec.

If these values are substituted in eqns. (8)–(10), which give the velocities in terms of the winding capacitances and inductances, the following values for the winding inductances are obtained:

Outer conductors: $L_3 = 41\cdot8\ \mu$H/bar.
Inner–outer conductors: $L_2 - L_3 = 13\ \mu$H/bar.
Inner conductors: $L_2 = 54\cdot8\ \mu$H/bar.
Bull–inner conductors: $L_1 - L_2 = 29\cdot3\ \mu$H/bar.
Bull conductors: $L_1 = 84\cdot1\ \mu$H/bar.

(4.3) Winding Surge Impedances

When calculating the theoretical response of the winding it is necessary to know the surge impedances of each section of the winding. These are defined in eqns. (14)–(16) in terms of the winding parameters, and may therefore be evaluated as follows:

$$Z_{12} = \sqrt{\left(\frac{L_1 - L_2}{C_1}\right)} = 35\cdot9 \text{ ohms}$$

$$Z_{23} = \sqrt{\left(\frac{L_2 - L_3}{C_2}\right)} = 20\cdot8 \text{ ohms}$$

$$Z_3 = \sqrt{\left(\frac{L_3}{C_3}\right)} = 142 \text{ ohms}$$

These values may be substituted in eqn. (189) to obtain a value of 117·3 ohms for the effective surge impedance of the alternator.

(5) COMPARISON OF TEST RESULTS WITH THEORY

The comparison of the test results with the theoretical deductions may take two forms—a comparison between anticipated and actual voltage distributions and a comparison between measurable and calculable circuit values.

(5.1) Impulse-Voltage Distribution

In a machine winding it is, unfortunately, impossible to calculate the impulse-voltage distribution beyond the first fraction of a microsecond without involving an excessive amount of tedious work; however, the theoretical deductions enable the test results to be explained.

The voltage-distribution curves for the various test conditions are very similar in the initial stages. In every case it will be seen that voltage waves are set up in all three sections of the winding at bar 28 corresponding to the bull conductor nearest to the terminal, the initial voltages being given by eqns. (184)–(187). With the various values for the circuit parameters given in the previous Section the theoretical voltages to earth are as given in the second column in Table 1.

The above test results are taken from the 1microsec voltage-distribution curves and appear to be rather low, and from the shape of the curves it would appear that this may be due to waves

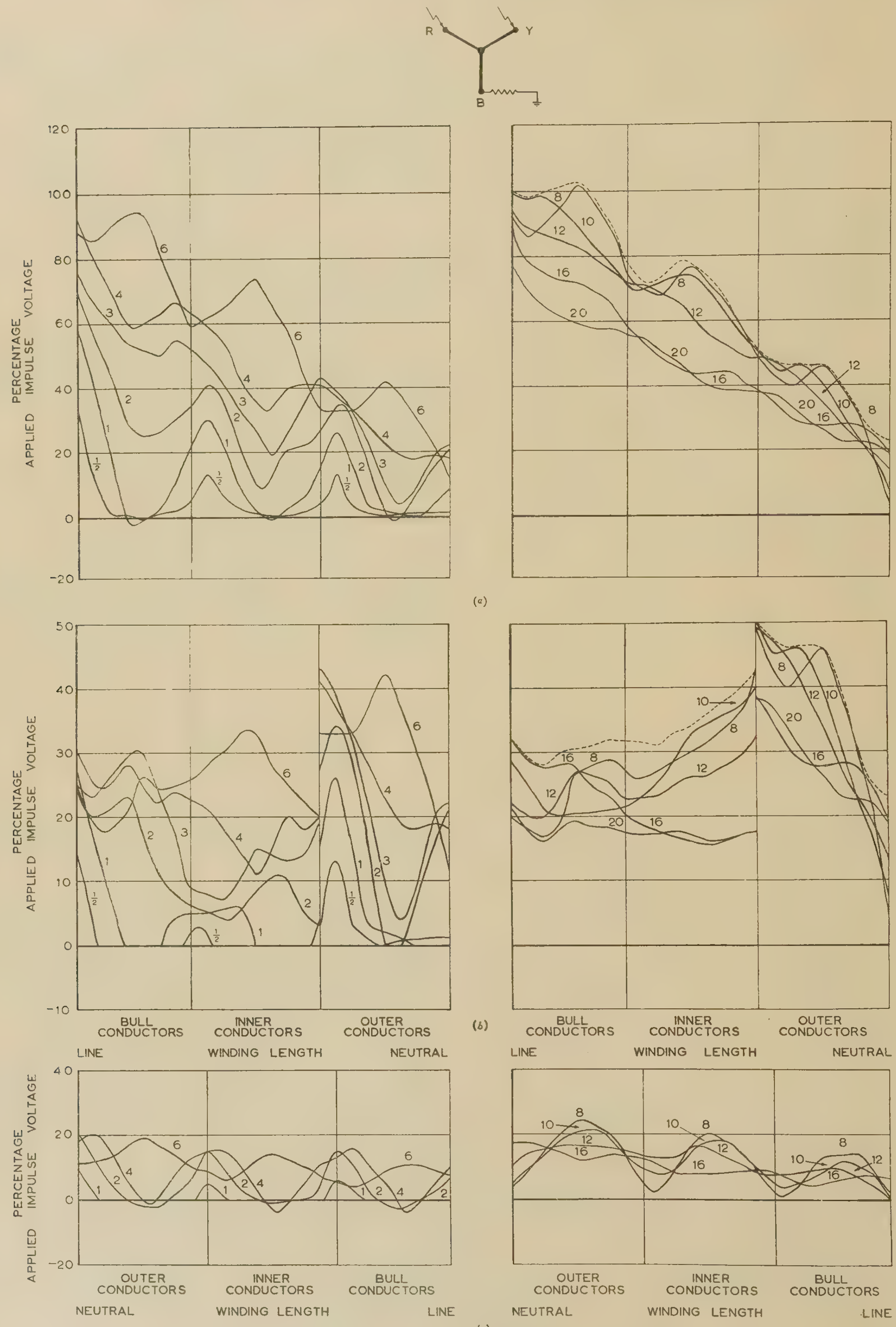

Fig. 4.—Impulse-voltage distribution in machine E; impulse applied to phases R and Y, neutral isolated.

(*a*) Phase R: voltage to earth.
(*b*) Phase R: voltage between conductors.
(*c*) Phase B: voltage to earth.

Figures on curves are times in microseconds.
Broken lines show maximum voltages.
Vertical lines indicate position of links.

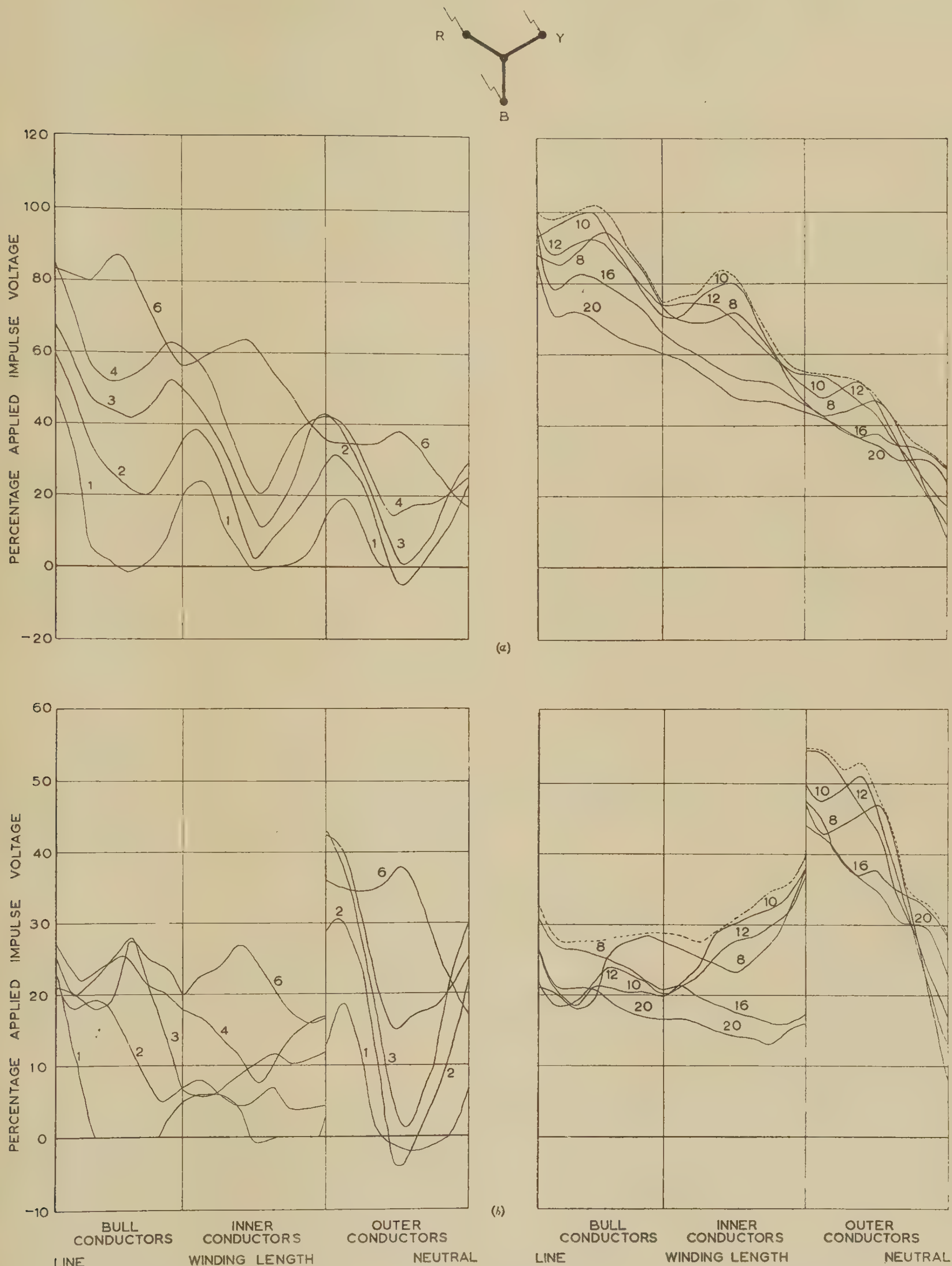

Fig. 5.—Impulse-voltage distribution in machine E; impulse applied to all three phases, neutral point isolated.

(*a*) Voltage to earth.
(*b*) Voltage between conductors.
Figures on curves are times in microseconds.
Broken lines show maximum voltages.
Vertical lines indicate positions of links.

Table 1

	Voltage to earth: Percentage of applied impulse	
	Theoretical	Test
	%	%
Bull conductors	100	100
Inner conductors	70	50
Outer conductors	60	41

reflected from the adjoining links. It may also be due to the fact that the incoming wave in the bull conductors is drawn with a sharp point and the distribution curves in the inners and outers have rounded crests.

The above induced voltages travel through the winding in both directions, but the velocity of propagation in the outer conductors is much lower, owing to the greater inductance of these conductors caused by the presence of iron in the return circuit. From Fig. 2 it will be seen that the wave entering the bull conductors reaches the bull–inner link in about 2·5 microsec, and the initial wave in the inner conductors reaches the inner–outer link in just less than 2 microsec. However, the wave in the outer conductors requires about 7 or 8 microsec to reach the neutral point. Subsequent reflections and refractions occur at the links and at the neutral point, producing voltages in all the sections of the winding. The maximum voltage gradient at the neutral point occurs as the outer-conductor wave reaches the neutral. The next high-voltage gradient at the neutral point occurs at about 16 microsec, which corresponds to the arrival and partial reflection of the wave which has travelled through the winding from the phase terminal. The foot reaches the neutral after about 12 microsec, but the maximum gradient occurs after this, since the summation of the incoming and reflected waves produces a steeper gradient. The voltage gradient itself depends on the steepness of the travelling wavefront and decreases with time owing to the dispersal produced by the varying velocities of the sinusoidal components of the initial applied voltage.

The distribution curves for the single- and 2-phase impulse voltages have the same general shape, but the voltages are somewhat lower with the 2-phase impulse, owing to the lower effective impedance of the alternator compared with the impulse generator, which was unaltered throughout the tests.

If the neutral point is isolated, voltages appear at the neutral in the first few microseconds which are induced by the waves in the bull and inner conductors travelling in the reverse direction from the points of induction (bar 28) in the inner and outer conductors. This is clearly shown in Fig. 4 and appears to occur for about the first four microseconds, when the forward-travelling wave from the outer conductor (bar 28) begins to exert an overwhelming influence.

With a 2-phase impulse (Fig. 4) the voltage distributions in the two impulsed phases are similar, since there is no significant mutual coupling between phases. This is as would be expected, since each phase is restricted to its own section of the core and each conductor bar is in its own slot. Since the neutral point is isolated, voltage waves will travel through the neutral connection into the unimpulsed phase. The voltages induced in this winding take the form of oscillations in each section of the winding at a frequency corresponding to the travelling waves in the outer conductors. The bull and inner conductors appear to have little influence, and their voltage appears to be effectively limited by the 500-ohm terminal resistor used to simulate an overhead line. If this resistor had been omitted, it is probable that higher voltages would have occurred in these sections, owing to t various reflections.

With a 3-phase impulse and the neutral point isolated it mig be anticipated that the worst conditions would occur. T voltage-distribution curves in Fig. 5 show that the maximu voltage occurring at the neutral point is only about 30% of t applied impulse voltage, and the maximum voltage whi occurred in the outer conductors was approximately 55% of t applied voltage.

It will be noted that the voltage distribution in the windi becomes approximately linear after the first 10 microsec and th nearly all the maximum voltages occur at about 8 microse owing to the reflections in the windings.

(5.2) Winding Surge Impedance

The winding surge impedance was measured directly inserting a resistor between the impulse generator and the stat The initial voltages on either side of this resistor were recorde and the surge impedance was calculated as described in a previo paper.[2] With a single-phase impulse this gave values of 126 ohi with the neutral isolated and 114 ohms with the neutral earthe Slightly higher values were obtained with 2- and 3-phase impuls with the neutral isolated, the highest being 145 ohms for a 3-pha impulse. All results with the neutral earthed agreed within 1 2%. These compare with a calculated value of 117·3 ohms.

The effect of isolating the neutral is shown in the theoretic case only when all three sections of the winding have the sa number of conductor bars. The test results indicate, howev that the four conductor bars separating the line terminal fro the links (and thus the neutral point) are not sufficient to preve reflected waves from the links (and thus indirectly from t neutral point) affecting the winding surge impedance.

(5.3) Critical Frequency

Tests similar to those described in the previous paper[1] we made to determine the critical frequency of the winding, exce that a line about 25 yd long was used between the impul generator and the alternator. These unfortunately did n permit a very accurate estimate of the critical frequency to made, but were sufficient to indicate that it lay between abo 350 and 800 kc/s, which correspond to wavefronts of 0· 0·8 microsec.

Assuming a capacitance of 200 $\mu\mu$F between adjacent en windings and substituting the values of inductance in eqn. (7 a critical frequency of 850 kc/s is obtained, which is of the sa order as that obtained from the experimental results.

(6) CONCLUSIONS

The foregoing investigation leads to a better appreciation the phenomena occurring during the penetration of su voltages into concentric-conductor-type windings of rotati machines. It enables an approximate equivalent circuit for t winding to be devised and analysed in a way which is not possib using the orthodox standing-wave method of analysis for t study of surge voltages.[7–9]

When a surge voltage reaches the machine terminals a set travelling voltage waves is set up between each pair of adjace conductors, each wave travelling with a velocity characteris of the conductors and the intervening insulation or tube. T voltage wave between the outer conductor and the core has t lowest velocity, owing to the increased inductance produced the iron.

When a wave reaches the end of a section of the windi reflection and refraction occur, inducing voltages, not only

the two sections or conductors concerned, but also in the corresponding point in the other conductors. Thus a voltage wave between the bull and inner conductors approaching the bull-inner link will, on reflection, set up waves at either side of this link and at the same time induce voltages at either side of the inner-outer link and at the neutral point. This causes the travelling-wave system to increase rapidly in complexity and to render any attempt to predict voltages theoretically extremely tedious if not impossible.

The surge impedance of the machine tested was about 115 ohms, which compares with the figure of 125 ohms given previously[10] for another machine which was tested without its rotor. Theoretical considerations indicate that if, as is now general practice, all the bull conductors had been connected in circuit, the surge impedance of the machine would have been lower. Unfortunately it has not been possible to confirm this experimentally.

The low value of the machine surge impedance compared with a transmission line will reduce by reflection the amplitude of any surge approaching the machine from an overhead line. Subsequent reflections may cause the voltage to increase, but since the voltage distribution in the machine becomes approximately linear after about 10 microsec, the stresses produced will be fairly uniformly distributed in the machine.

In common with other large machines there is little possibility of damage from steep-fronted waves. In the concentric type the high capacitance between the various sections of the winding provides an efficient means of distributing the stress. In addition, the fact that the winding has a critical frequency of about 800 kc/s prevents any steep-fronted wave entering the winding.

The most effective form of surge protection for a machine of this type would appear to be a voltage-limiting type of surge arrester or gap which would prevent the machine terminal voltage reaching dangerous levels. From the tests it would appear that earthing of the neutral point does not appreciably affect the surge-voltage stresses in the machine. In the 25 years since the first machine of this type was installed, operating experience has not shown any breakdowns which can be attributed to surge voltages. This may be regarded as reliable evidence of the satisfactory nature of the general design.

(7) ACKNOWLEDGMENTS

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(9) APPENDIX

(9.1) Theory of Propagation of a Surge through a Concentric Conductor Alternator

The equivalent circuit for a concentric-conductor alternator is shown in Fig. 1. Assume that each unit consists of a complete coil, namely two conductor bars and their equivalent end-windings. The three sections of the winding will run parallel throughout their length. In order to obtain differential equations it is necessary to assume that the circuit constants are uniformly distributed throughout the length instead of being divided between the conductor bars and end-windings.

Consider the currents flowing in an element δx at a distance x from the terminal. The current flowing from the bull conductor to the inner conductor will be

$$C_1\left(\frac{\partial v_1}{\partial t} - \frac{\partial v_2}{\partial t}\right)\delta x \quad . \quad . \quad . \quad . \quad . \quad (26)$$

The current flowing between turns of the same winding, i.e. between coils of bull conductors, may be derived[1] as

$$- C_t l^2 \frac{\partial^3 v_1}{\partial x^2 \partial t}\delta x \quad . \quad . \quad . \quad . \quad . \quad (27)$$

Hence the loss in current from the element δx will be

$$- \delta I_1 = C_1\left(\frac{\partial v_1}{\partial t} - \frac{\partial v_2}{\partial t}\right)\delta x - C_t l^2 \frac{\partial^3 v_1}{\partial x^2 \partial t}\delta x \quad . \quad (28)$$

Or expressing it in differentials

$$- \frac{\partial I_1}{\partial x} = C_1\left(\frac{\partial v_1}{\partial t} - \frac{\partial v_2}{\partial t}\right) - C_t l^2 \frac{\partial^3 v_1}{\partial x^2 \partial t} \quad . \quad . \quad (29)$$

Now consider the second or inner conductor. The current flowing to the bull conductor will be

$$- C_1\left(\frac{\partial v_1}{\partial t} - \frac{\partial v_2}{\partial t}\right)\delta x \, . \quad . \quad . \quad . \quad . \quad (30)$$

and that to the outer

$$C_2\left(\frac{\partial v_2}{\partial t} - \frac{\partial v_3}{\partial t}\right)\delta x \quad . \quad . \quad . \quad . \quad . \quad (31)$$

Hence the current equation for the inner conductor becomes

$$- \frac{\partial I_2}{\partial x} = - C_1 \frac{\partial v_1}{\partial t} + (C_1 + C_2)\frac{\partial v_2}{\partial t} - C_2 \frac{\partial v_3}{\partial t} - C_t l^2 \frac{\partial^3 v_2}{\partial x^2 \partial t} \quad . \quad (32)$$

Similarly for the outer conductor

$$- \frac{\partial I_3}{\partial x} = - C_2 \frac{\partial v_2}{\partial t} + (C_2 + C_3)\frac{\partial v_3}{\partial t} - C_t l^2 \frac{\partial^3 v_3}{\partial x^2 \partial t} \quad . \quad (33)$$

Now consider the voltage equations

$$-\frac{\partial v_1}{\partial x} = L_1\frac{\partial I_1}{\partial t} + M_{12}\frac{\partial I_2}{\partial t} + M_{13}\frac{\partial I_3}{\partial t} \quad . \quad . \quad . \quad (34)$$

$$-\frac{\partial v_2}{\partial x} = M_{12}\frac{\partial I_1}{\partial t} + L_2\frac{\partial I_2}{\partial t} + M_{23}\frac{\partial I_3}{\partial t} \quad . \quad . \quad . \quad (35)$$

$$-\frac{\partial v_3}{\partial x} = M_{13}\frac{\partial I_1}{\partial t} + M_{23}\frac{\partial I_2}{\partial t} + L_3\frac{\partial I_3}{\partial t} \quad . \quad . \quad (36)$$

Differentiate eqns. (29), (32) and (33) with respect to t, and (34), (35) and (36) with respect to x, and substitute:

$$\frac{\partial^2 v_1}{\partial x^2} = L_1\left[C_1\left(\frac{\partial^2 v_1}{\partial t^2} - \frac{\partial^2 v_2}{\partial t^2}\right) - C_t l^2\frac{\partial^4 v_1}{\partial x^2 \partial t^2}\right]$$
$$+ M_{12}\left[-C_1\frac{\partial^2 v_1}{\partial t^2} + (C_1 + C_2)\frac{\partial^2 v_2}{\partial t^2} - C_2\frac{\partial^2 v_3}{\partial t^2} - C_t l^2\frac{\partial^4 v^2}{\partial x^2 \partial t^2}\right]$$
$$+ M_{13}\left[-C_2\frac{\partial^2 v_2}{\partial t^2} + (C_2 + C_3)\frac{\partial^2 v_3}{\partial t^2} - C_t l^2\frac{\partial^4 v_3}{\partial x^2 \partial t^2}\right] \quad . \quad (37)$$
$$= (L_1C_1 - M_{12}C_1)\frac{\partial^2 v_1}{\partial t^2} + (-L_1C_1 + M_{12}C_1 + M_{12}C_2$$
$$- M_{13}C_2)\frac{\partial^2 v_2}{\partial t^2} + (-M_{12}C_2 + M_{13}C_2 + M_{13}C_3)\frac{\partial^2 v_3}{\partial t^2}$$
$$- C_t l^2\left(L_1\frac{\partial^4 v_1}{\partial x^2 \partial t^2} + M_{12}\frac{\partial^4 v_2}{\partial x^2 \partial t^2} + M_{13}\frac{\partial^4 v_3}{\partial x^2 \partial t^2}\right) \quad . \quad (38)$$

$$\frac{\partial^2 v_2}{\partial x^2} = (M_{12}C_1 - L_2C_1)\frac{\partial^2 v_1}{\partial t^2} + (-M_{12}C_1 + L_2C_1 + L_2C_2$$
$$- M_{23}C_2)\frac{\partial^2 v_2}{\partial t^2} + (-L_2C_2 + M_{23}C_2 + M_{23}C_3)\frac{\partial^2 v_3}{\partial t^2}$$
$$- C_t l^2\left(M_{12}\frac{\partial^4 v_1}{\partial x^2 \partial t^2} + L_2\frac{\partial^4 v_2}{\partial x^2 \partial t^2} + M_{23}\frac{\partial^4 v_3}{\partial x^2 \partial t^2}\right) \quad . \quad (39)$$

$$\frac{\partial^2 v_3}{\partial x^2} = (M_{13}C_1 - M_{23}C_1)\frac{\partial^2 v_1}{\partial t^2} + (-M_{13}C_1 + M_{23}C_1 + M_{23}C_2$$
$$- L_3C_2)\frac{\partial^2 v_2}{\partial t^2} + (-M_{23}C_2 + L_3C_2 + L_3C_3)\frac{\partial^2 v_3}{\partial t^2}$$
$$- C_t l^2\left(M_{13}\frac{\partial^4 v_1}{\partial x^2 \partial t^2} + M_{23}\frac{\partial^4 v_2}{\partial x^2 \partial t^2} + L_3\frac{\partial^4 v_3}{\partial x^2 \partial t^2}\right) \quad . \quad (40)$$

Assume solutions of the form

$$v = V\varepsilon^{j\omega\left(t - \frac{x}{u}\right)} \quad . \quad . \quad . \quad . \quad . \quad (4$$

Substitute in eqns. (38), (39), (40) and multiply by $\frac{-u^2}{\omega^2}\varepsilon^{j\omega\left(t - \frac{x}{u}\right)}$

$$V_1 = (L_1C_1 - M_{12}C_1)u^2V_1 + (-L_1C_1 + M_{12}C_1 + M_{12}C_2$$
$$- M_{13}C_2)u^2V_2 + (-M_{12}C_2 + M_{13}C_2 + M_{13}C_3)u^2V_3$$
$$+ C_t l^2\omega^2(L_1V_1 + M_{12}V_2 + M_{13}V_3) \quad . \quad . \quad . \quad . \quad (4$$

$$V_2 = (M_{12}C_1 - L_2C_1)u^2V_1 + (-M_{12}C_1 + L_2C_1 + L_2C_2$$
$$- M_{23}C_2)u^2V_2 + (-L_2C_2 + M_{23}C_2 + M_{23}C_3)u^2V_3$$
$$+ C_t l^2\omega^2(M_{12}V_1 + L_2V_2 + M_{23}V_3) \quad . \quad . \quad . \quad . \quad (4$$

$$V_3 = (M_{13}C_1 - M_{23}C_1)u^2V_1 + (-M_{13}C_1 + M_{23}C_1 + M_{23}C_2$$
$$- L_3C_2)u^2V_2 + (-M_{23}C_2 + L_3C_2 + L_3C_3)u^2V_3$$
$$+ C_t l^2\omega^2(M_{13}V_1 + M_{23}V_2 + L_3V_3) \quad . \quad . \quad . \quad . \quad (4$$

These general equations cannot be solved to obtain t relation between u^2 and ω^2. However, as explained in Section 2. an approximate solution may be obtained for small values o by letting ω tend to zero, when the equations become

$$\left(L_1C_1 - M_{12}C_1 - \frac{1}{u^2}\right)V_1$$
$$+ (-L_1C_1 + M_{12}C_1 + M_{12}C_2 - M_{13}C_2)V_2$$
$$+ (-M_{12}C_2 + M_{13}C_2 + M_{13}C_3)V_3 = 0 \quad . \quad (4$$

$$(M_{12}C_1 - L_2C_1)V_1$$
$$+ \left(-M_{12}C_1 + L_2C_1 + L_2C_2 - M_{23}C_2 - \frac{1}{u^2}\right)V_2$$
$$+ (-L_2C_2 + M_{23}C_2 + M_{23}C_3)V_3 = 0 \quad . \quad (4$$

$$(M_{13} - M_{23})C_1V_1$$
$$+ [-(M_{13} - M_{23})C_1 + (M_{23} - L_3)C_2]V_2$$
$$+ \left[-(M_{23} - L_3)C_2 + L_3C_3 - \frac{1}{u^2}\right]V_3 = 0 \quad . \quad (4$$

These three equations must be valid simultaneously, and si V_1, V_2, V_3 are not zero the following determinant must be zer

$$\begin{vmatrix} (L_1 - M_{12})C_1 - \frac{1}{u^2} & -(L_1 - M_{12})C_1 + (M_{12} - M_{13})C_2 & -(M_{12} - M_{13})C_2 + M_{13}C_3 \\ (M_{12} - L_2)C_1 & -(M_{12} - L_2)C_1 + (L_2 - M_{23})C_2 - \frac{1}{u^2} & -(L_2 - M_{23})C_2 + M_{23}C_3 \\ (M_{13} - M_{23})C_1 & -(M_{13} - M_{23})C_1 + (M_{23} - L_3)C_2 & -(M_{23} - L_3)C_2 + L_3C_3 - \frac{1}{u^2} \end{vmatrix} = 0 \quad . \quad . \quad (4$$

Multiplying out gives

$$\{[(L_1 - M_{12})(L_2 - M_{23}) + (L_2 - M_{12})(M_{12} - M_{13})]L_3 + [(L_1 - M_{12})(L_3 - M_{23}) + (M_{13} - M_{23})(M_{12} - M_{13})]M_{23}$$
$$+ [(L_2 - M_{12})(L_3 - M_{23}) - (M_{13} - M_{23})(L_2 - M_{23})M_{13}]\}C_1C_2C_3 - \frac{1}{u^2}\{[(L_2 - M_{12})(L_3 - M_{23})$$
$$+ (L_2 - M_{12})(M_{12} - M_{13}) + (M_{13} - M_{23})(M_{12} - M_{23}) - (L_2 - M_{23})(M_{13} - M_{23}) + (L_1 - M_{12})(L_2 - M_{23})$$
$$+ (L_1 - M_{12})(L_3 - M_{23})]C_1C_2 + [L_3(L_2 - M_{12}) + M_{23}(M_{13} - M_{23}) + L_3(L_1 - M_{12}) - M_{13}(M_{13} - M_{23})]C_1C_3$$
$$+ [L_3(L_2 - M_{23}) + M_{23}(L_3 - M_{23})]C_2C_3\} + \frac{1}{u^4}[(L_1 + L_2 - 2M_{12})C_1 + (L_2 + L_3 - 2M_{23})C_2 + L_3C_3] - \frac{1}{u^6} = 0 \quad . \quad ($$

This can be factorized only if $M_{12} = L_2$, $M_{13} = M_{23} = L_3$, which is approximately true as explained in Section 2.1:

$$\left(\frac{1}{u^2} - L_3C_3\right)\left[\frac{1}{u^2} - (L_1 - L_2)C_1\right]\left[\frac{1}{u^2} - (L_2 - L_3)C_2\right] = 0 \quad (50)$$

giving the three roots for the velocity as in eqns. (8)–(10).

Substitute these values in eqns. (45)–(47):

$\frac{1}{u_a^2} = (L_1 - L_2)C_1$ gives

$$0 \times V_1 + [-(L_1 - L_2)C_1 + (L_2 - L_3)C_2]V_2 + [-(L_2 - L_3)C_2 + L_3C_3]V_3 = 0 \quad (51)$$

$$0 \times V_1 + [(L_2 - L_3)C_2 - (L_1 - L_2)C_1]V_2 + [-(L_2 - L_3)C_2 - L_3C_3]V_3 = 0 \quad (52)$$

$$0 \times V_1 + 0 \times V_2 + [L_3C_3 - (L_1 - L_2)C_1]V_3 = 0 \quad (53)$$

which gives V_1 indeterminate, and

$$V_2 = V_3 = 0 \quad (54)$$

Similarly, substituting $\frac{1}{u_b^2} = (L_2 - L_3)C_2$ gives

$$[(L_1 - L_2)C_1 - (L_2 - L_3)C_2]V_1 + [-(L_1 - L_2)C_1 + (L_2 - L_3)C_2]V_2 + [-(L_2 - L_3)C_2 + L_3C_3]V_3 = 0 \quad (55)$$

$$0 \times V_1 + [(L_2 - L_3)C_2 - (L_2 - L_3)C_2]V_2 + [-(L_2 - L_3)C_2 + L_3C_3]V_3 = 0 \quad (56)$$

$$0 \times V_1 + 0 \times V_2 + [(L_3C_3) - (L_2 - L_3)C_2]V_3 = 0 \quad (57)$$

which gives $V_3 = 0, \quad V_1 = V_2 \quad (58)$

Substituting $\frac{1}{u_c^2} = L_3C_3$ gives

$$[(L_1 - L_2)C_1 - L_3C_3]V_1 + [-(L_1 - L_2)C_1 + (L_2 - L_3)C_2]V_2 + [-(L_2 - L_3)C_2 + L_3C_3]V_3 = 0 \quad (59)$$

$$0 \times V_1 + [(L_2 - L_3)C_2 - L_3C_3]V_2 + [-(L_2 - L_3)C_2 + L_3C_3]V_3 = 0 \quad (60)$$

$$0 \times V_1 + 0 \times V_2 + 0 \times V_3 = 0 \quad (61)$$

which gives $V_2 = V_3 = V_1 \quad (62)$

Hence we may write the approximate solutions to the differential equations as

$$v_1 = V_a\varepsilon^{j\omega\left(t - \frac{x}{u_a}\right)} + V_b\varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} + V_c\varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad (63)$$

$$v_2 = V_b\varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} + V_c\varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad (64)$$

$$v_3 = V_c\varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad (65)$$

It will be noted that the stress across the bull conductor is $V_a = v_1 - v_2$ and across the inners $V_b = v_2 - v_3$ and the outers $V_c = v_3$.

The voltages V_a, V_b and V_c are, strictly speaking, the amplitudes of the sinusoidal components of frequency $\omega = 0$. Since, as a mathematical approximation in this paper, all component frequencies of the travelling waves are assumed to have velocities of u_a, u_b and u_c, the symbols V_a, V_b and V_c are used to denote the amplitude of the waves produced by the summation of the sinusoidal components.

(9.2) Critical Frequency

Now, at the critical frequency, $u = 0$ and eqns. (42)–(44) give

$$V_1 = C_t l^2\omega^2(L_1V_1 + M_{12}V_2 + M_{13}V_3) \quad (66)$$

$$V_2 = C_t l^2\omega^2(M_{12}V_1 + L_2V_2 + M_{23}V_3) \quad (67)$$

$$V_3 = C_t l^2\omega^2(M_{13}V_1 + M_{23}V_2 + L_3V_3) \quad (68)$$

Writing $M_{12} = L_2$ and $M_{13} = M_{23} = L_3$ as before gives

$$V_1(C_t l^2\omega^2L_1 - 1) + V_2C_t l^2\omega^2L_2 + V_3C_t l^2\omega^2L_3 = 0 \quad (69)$$

$$V_1C_t l^2\omega^2L_2 + V_2(C_t l^2\omega^2L_2 - 1) + V_3C_t l^2\omega^2L_3 = 0 \quad (70)$$

$$V_1C_t l^2\omega^2L_3 + V_2C_t l^2\omega^2L_3 + V_3(C_t l^2\omega^2L_3 - 1) = 0 \quad (71)$$

Since V_1, V_2 and $V_3 \neq 0$, the determinant

$$\begin{vmatrix} KL_1 - 1 & KL_2 & KL_3 \\ KL_2 & KL_2 - 1 & KL_3 \\ KL_3 & KL_3 & KL_3 - 1 \end{vmatrix} = 0 \quad (72)$$

where $K = C_t l^2\omega^2 \quad (73)$

Multiplying out gives

$$(KL_1 - 1)(KL_2 - 1)(KL_3 - 1) + 2K^3L_2L_3^2 - (KL_1 - 1)K^2L_3^2 - (KL_3 - 1)K^2L_2^2 - K^2L_3^2(KL_2 - 1) = 0 \quad (74))$$

$$K^3L_1L_2L_3 - K^2(L_1L_2 + L_2L_3 + L_3L_1) + K(L_1 + L_2 + L_3) - 1 - 2K^3L_2L_3 - K^3L_1L_3^2 + K^2L_3^2 - K^3L_2^2L_3 + K^2L_2^2 - K^3L_2L_3^2 + K^2L_3^2 = 0 \quad (75)$$

$$K^3(L_1L_2L_3 - 3L_2L_3^2 - L_1L_3^2 - L_2^2L_3) - K^2(L_1L_2 + L_2L_3 + L_3L_1 - 2L_3^2 - L_2^2) + K(L_1 + L_2 + L_3) - 1 = 0 \quad (76)$$

This is soluble only in particular cases.

(9.3) Approximate Equations for the Propagation of Waves in the Winding

Introducing the approximations from eqn. (7) into eqns. (34)–(36):

$$-\frac{\partial v_1}{\partial x} = L_1\frac{\partial I_1}{\partial t} + L_2\frac{\partial I_2}{\partial t} + L_3\frac{\partial I_3}{\partial t} \quad (77)$$

$$-\frac{\partial v_2}{\partial x} = L_2\left(\frac{\partial I_1}{\partial t} + \frac{\partial I_2}{\partial t}\right) + L_3\frac{\partial I_3}{\partial t} \quad (78)$$

$$-\frac{\partial v_3}{\partial x} = L_3\left(\frac{\partial I_1}{\partial t} + \frac{\partial I_2}{\partial t} + \frac{\partial I_3}{\partial t}\right) \quad (79)$$

Subtracting these to obtain the intersection voltages gives

$$-\frac{\partial v_1}{\partial x} + \frac{\partial v_2}{\partial x} = -\frac{\partial v_{12}}{\partial x} = (L_1 - L_2)\frac{\partial I_1}{\partial t} \quad (80)$$

$$-\frac{\partial v_2}{\partial x} + \frac{\partial v_3}{\partial x} = -\frac{\partial v_{23}}{\partial x} = (L_2 - L_3)\left(\frac{\partial I_1}{\partial t} + \frac{\partial I_2}{\partial t}\right) \quad (81)$$

The solutions in eqns. (63) to (65) show that

$$v_{12} = V_a\varepsilon^{j\omega\left(t - \frac{x}{u_a}\right)} \quad (82)$$

$$v_{23} = V_b\varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} \quad (83)$$

$$v_3 = V_c\varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad (84)$$

Substituting these values in eqn. (80) yields

$$\frac{\partial I_1}{\partial t} = \frac{1}{L_1 - L_2}\left[\frac{j\omega}{u_a} V_a \varepsilon^{j\omega\left(t - \frac{x}{u_a}\right)}\right] \quad . \quad . \quad . \quad (85)$$

$$I_1 = \frac{1}{L_1 - L_2}\frac{1}{u_a} V_a \varepsilon^{j\omega\left(t - \frac{x}{u_a}\right)} \quad . \quad . \quad . \quad . \quad (86)$$

$$= \sqrt{\left(\frac{C_1}{L_1 - L_2}\right)} V_a \varepsilon^{j\omega\left(t - \frac{x}{u_a}\right)} \quad . \quad . \quad . \quad (87)$$

or

$$v_{12} = Z_{12} I_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (88)$$

where

$$Z_{12} = \sqrt{\left(\frac{L_1 - L_2}{C_1}\right)} \quad . \quad . \quad . \quad . \quad . \quad (89)$$

Similarly with eqn. (81):

$$\frac{\partial I_1}{\partial t} + \frac{\partial I_2}{\partial t} = \frac{1}{L_2 - L_3}\frac{j\omega}{u_b} V_b \varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} \quad . \quad . \quad (90)$$

$$I_1 + I_2 = \frac{1}{L_2 - L_3}\frac{1}{u_b} V_b \varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} \quad . \quad . \quad . \quad (91)$$

$$= \sqrt{\left(\frac{C_2}{L_2 - L_3}\right)} V_b \varepsilon^{j\omega\left(t - \frac{x}{u_b}\right)} \quad . \quad . \quad (92)$$

or

$$v_{23} = Z_{23}(I_1 + I_2) \quad . \quad . \quad . \quad . \quad . \quad (93)$$

where

$$Z_{23} = \sqrt{\left(\frac{L_2 - L_3}{C_2}\right)} \quad . \quad . \quad . \quad . \quad . \quad (94)$$

Similarly from eqn. (79):

$$I_1 + I_2 + I_3 = \sqrt{\left(\frac{C_3}{L_3}\right)} V_c \varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad . \quad . \quad (95)$$

$$= Z_3 V_c \varepsilon^{j\omega\left(t - \frac{x}{u_c}\right)} \quad . \quad . \quad . \quad . \quad (96)$$

or

$$v_3 = Z_3(I_1 + I_2 + I_3) \quad . \quad . \quad . \quad . \quad (97)$$

where

$$Z_3 = \sqrt{\left(\frac{L_3}{C_3}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (98)$$

(9.4) Derivation of the Magnitudes of the Initial Travelling Waves

Assume that the machine is full wound, i.e. there are equal numbers of bull, inner and outer conductors, as is the case with all machines of the latest design. The arrival of a travelling wave V_{line} at the terminal sets up travelling waves in the bull, inner and outer conductors as shown in Fig. 6.

Let v_{A12}, v_{B23}, v_{C3} and v_{Dn} be the waves travelling forward, i.e. into the winding, and let v'_{B12}, v'_{C23}, v'_{D3} be the waves travelling in the reverse direction, the letter suffix denoting the point of origin of the wave, i.e. the line terminal (A), the bull-inner link (B), the inner-outer link (C) and the star point (D), and the numeral suffix denoting the conductors concerned, as before, i.e. v_{12} denoting the voltage between the bull and inner conductors.* The conditions may then be expressed algebraically as follows:

$$V_{line} = v_{A12} + v_{B23} + v_{C3} \quad . \quad . \quad . \quad (99)$$

$$v'_{B12} = v_{B23} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (100)$$

$$v'_{C23} + v'_{D3} = v_{C3} \quad . \quad . \quad . \quad . \quad . \quad (101)$$

$$v'_{D3} = v_{Dn} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (102)$$

* The sign convention used for the travelling waves is as follows:
(a) The sums of the voltages on both sides of a junction are equal.
(b) At any junction the incoming currents equal the outgoing currents.
(c) In general $v = IZ$.

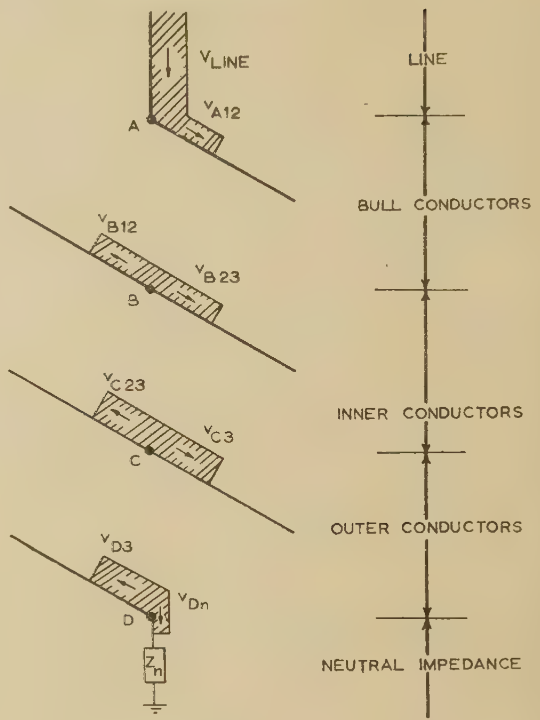


Fig. 6.—Diagram showing voltages induced by incoming surge V_{li}

Using the similar notation for the currents

$$I'_{B1} + I_{B2} = 0 \quad . \quad . \quad . \quad . \quad . \quad (10$$

$$I'_{C2} + I_{C3} = 0 \quad . \quad . \quad . \quad . \quad . \quad (10$$

$$I'_{D3} + I_{Dn} = 0 \quad . \quad . \quad . \quad . \quad . \quad (10$$

And, from eqns. (88), (93) and (97),

$$v_{A12} = Z_{12} I_{A1} \quad . \quad . \quad . \quad . \quad . \quad (10$$

$$v'_{B12} = Z_{12} I'_{B1} \quad . \quad . \quad . \quad . \quad . \quad (10$$

$$v_{B23} = Z_{23}(I_{B2} + I_{A1}) \quad . \quad . \quad . \quad . \quad (10$$

or

$$I_{B2} = \frac{v_{B23}}{Z_{23}} - \frac{v_{A12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (10$$

Similarly,

$$I'_{C2} = \frac{v'_{C23}}{Z_{23}} - \frac{v'_{B12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (11$$

$$I_{C3} = \frac{v_{C3}}{Z_3} - \frac{v_{B23}}{Z_{23}} \quad . \quad . \quad . \quad . \quad . \quad (11$$

$$I'_{D3} = \frac{v'_{D3}}{Z_3} - \frac{v'_{C23}}{Z_{23}} \quad . \quad . \quad . \quad . \quad . \quad (11$$

$$I_n = \frac{v_n}{Z_n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1$$

where Z_n is the impedance to earth at the neutral point.

Eliminating the currents in eqns. (103)–(105) with eq (106)–(113) gives

$$\frac{v'_{B12}}{Z_{12}} + \frac{v_{B23}}{Z_{23}} - \frac{v_{A12}}{Z_{12}} = 0 \quad . \quad . \quad . \quad . \quad (1$$

$$\frac{v'_{C23}}{Z_{23}} - \frac{v'_{B12}}{Z_{12}} + \frac{v_{C3}}{Z_3} - \frac{v_{B23}}{Z_{23}} = 0 \quad . \quad . \quad . \quad (1$$

$$\frac{v'_{D3}}{Z_3} - \frac{v'_{C23}}{Z_{23}} + \frac{v_{Dn}}{Z_n} = 0 \quad . \quad . \quad . \quad . \quad (116)$$

Now eliminating the reverse waves with eqns. (100)–(102) gives

$$\frac{v_{B23}}{Z_{12}} + \frac{v_{B23}}{Z_{23}} - \frac{v_{A12}}{Z_{12}} = 0 \quad . \quad . \quad . \quad . \quad (117)$$

$$\frac{v_{C3}}{Z_{23}} - \frac{v_{Dn}}{Z_{23}} - \frac{v_{B23}}{Z_{12}} + \frac{v_{C3}}{Z_3} - \frac{v_{B23}}{Z_{23}} = 0 \quad . \quad . \quad (118)$$

$$\frac{v_{Dn}}{Z_3} - \frac{v_{C3}}{Z_{23}} + \frac{v_{Dn}}{Z_{23}} + \frac{v_{Dn}}{Z_n} = 0 \quad . \quad . \quad . \quad (119)$$

Rearranging these gives

$$\frac{v_{Dn}}{v_{C3}} = \frac{Z_3Z_n}{Z_3Z_{23} + Z_3Z_n + Z_nZ_{23}} \quad . \quad . \quad . \quad (120)$$

$$= \frac{1}{1 + Z_{23}\left(\frac{Z_3 + Z_n}{Z_3Z_n}\right)} \quad . \quad . \quad . \quad . \quad (121)$$

$$v_{C3}\left(\frac{1}{Z_{23}} + \frac{1}{Z_3}\right) - \frac{v_{Dn}}{Z_{23}} = v_{B23}\left(\frac{1}{Z_{12}} + \frac{1}{Z_{23}}\right) \quad . \quad (122)$$

Substitute eqn. (121) to eliminate v_{Dn}:

$$v_{C23}\left[\frac{Z_{23} + Z_3}{Z_{23}Z_3} - \frac{1}{Z_{23} + Z_{23}^2\left(\frac{Z_3 + Z_n}{Z_3Z_n}\right)}\right] = v_{B23}\left(\frac{Z_{12} + Z_{23}}{Z_{12}Z_{23}}\right) \quad . \quad . \quad . \quad . \quad (123)$$

$$\frac{v_{C3}}{v_{B23}} = \frac{Z_{12} + Z_{23}}{Z_{12}}\frac{Z_3}{Z_{23}}\left[1 - \frac{Z_3(Z_3 + Z_n)}{Z_3Z_n + (Z_{23} + Z_3)(Z_3 + Z_n)}\right] \quad . \quad (124)$$

From eqn. (117)

$$v_{B23}\left(\frac{1}{Z_{12}} + \frac{1}{Z_{23}}\right) = \frac{v_{A12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad (125)$$

$$\frac{v_{B23}}{v_{A12}} = \frac{Z_{23}}{Z_{12} + Z_{23}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (126)$$

Substituting this in eqn. (124) gives

$$\frac{v_{C3}}{v_{A12}} = \frac{Z_3}{Z_{12}}\left[1 - \frac{Z_3(Z_3 + Z_n)}{Z_3Z_n + (Z_{23} + Z_3)(Z_3 + Z_n)}\right] \quad . \quad (127)$$

Substitute eqns. (126) and (127) in eqn. (99) to obtain the relation between v_{A12} and the terminal voltage V_{line}:

$$V_{line} = \left\{1 + \frac{Z_{23}}{Z_{12} + Z_{23}} + \frac{Z_3}{Z_{12}}\left[1 - \frac{Z_3(Z_3 + Z_n)}{Z_3Z_n + (Z_{23} + Z_3)(Z_3 + Z_n)}\right]\right\}v_{A12} \quad . \quad . \quad . \quad . \quad (128)$$

Eqns. (121), (126), (127) and (128) then give the complete initial voltage distribution.

(9.5) Surge Impedance of the Winding

The surge impedance of the winding may be defined as the ratio of the applied voltage and the ingoing current, i.e.

$$Z_W = \frac{V_{line}}{I_{A1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (129)$$

which for the low-frequency components may be obtained from eqn. (106):

$$Z_W = Z_{12}\frac{V_{line}}{v_{A12}} \quad . \quad . \quad . \quad . \quad . \quad (130)$$

Substituting from eqn. (128) gives

$$Z_W = Z_{12} + \frac{Z_{12}Z_{23}}{Z_{12} + Z_{23}} + Z_3 - \frac{Z_3^2(Z_3 + Z_n)}{Z_3Z_n + (Z_{23} + Z_3)(Z_3 + Z_n)} \quad . \quad . \quad . \quad . \quad (131)$$

$$= Z_{12} + \frac{Z_{12}Z_{23}}{Z_{12} + Z_{23}} + Z_3 - \frac{Z_3^2}{Z_{23} + Z_3 + \frac{Z_3Z_n}{Z_3 + Z_n}} \quad . \quad (132)$$

This may be shown to be identical with Friedländer's expression for the surge impedance of a concentric-conductor winding.[3]

(9.6) Reflection of Incoming Waves at the Links

The distribution of a wave entering the winding from the line terminal having been considered, it is now necessary to consider what happens when the waves thus set up in the winding reach the next link between sections of the winding. Owing to the different velocities of the waves in the various sections, this will occur at different times. It is, however, proposed to assume that the waves all reach the links simultaneously, in order to obtain

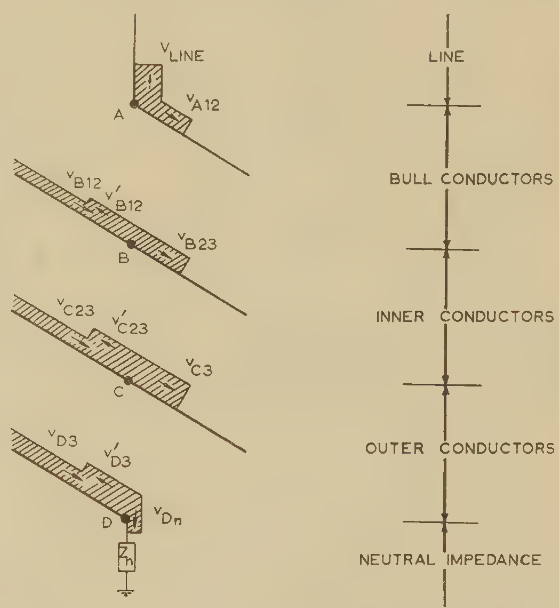


Fig. 7.—Diagram showing reflection of forward travelling waves at the links.

general formulae. Particular cases with only one wave reaching a link can then be obtained by putting the other incoming waves equal to zero. Write down the equations for the conditions at the various links and terminals as shown in Fig. 7.

Line terminal:

$$V_{line} = v_{A12} + v_{B23} + v_{C3} \quad . \quad . \quad . \quad (133)$$

$$= -Z_{12}I_{A1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (134)$$

Bull–inner link:

$$v_{B12} + v'_{B12} = v_{B23} \quad . \quad . \quad . \quad . \quad . \quad (135)$$

$$I_{B1} - I'_{B1} = I_{B2} \quad . \quad . \quad . \quad . \quad . \quad (136)$$

Inner–outer link:

$$v_{C23} + v'_{C23} + v_{D3} + v'_{D3} = v_{C3} \quad . \quad . \quad . \quad (137)$$

$$I_{C2} - I'_{C2} = I_{C3} \quad . \quad . \quad . \quad . \quad . \quad (138)$$

Neutral point:

$$v_{D3} + v'_{D3} = v_{Dn} \quad . \quad . \quad . \quad . \quad . \quad (139)$$

$$I_{D3} - I'_{D3} = I_{Dn} \quad . \quad . \quad . \quad . \quad . \quad (140)$$

And the general propagation equations:

$$v_{A12} = Z_{12} I_{A1} \quad . \quad . \quad . \quad . \quad . \quad (141)$$

$$I_{B1} = \frac{v_{B12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (142)$$

$$I'_{B1} = \frac{v'_{B12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (143)$$

$$I_{B2} = \frac{v_{B23}}{Z_{23}} - \frac{v_{A12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (144)$$

$$I_{C2} = \frac{v_{C23}}{Z_{23}} - \frac{v_{B12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (145)$$

$$I'_{C2} = \frac{v'_{C23}}{Z_{23}} - \frac{v'_{B12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad . \quad (146)$$

$$I_{C3} = \frac{v_{C3}}{Z_3} - \frac{v_{B23}}{Z_{23}} \quad . \quad . \quad . \quad . \quad . \quad (147)$$

$$I_{D3} = \frac{v_{D3}}{Z_3} - \frac{v_{C23}}{Z_{23}} \quad . \quad . \quad . \quad . \quad . \quad (148)$$

$$I'_{D3} = \frac{v'_{D3}}{Z_3} - \frac{v'_{C23}}{Z_{23}} \quad . \quad . \quad . \quad . \quad . \quad (149)$$

$$I_{Dn} = \frac{v_{Dn}}{Z_n} \quad . \quad . \quad . \quad . \quad . \quad (150)$$

Eliminating the currents from eqns. (134), (136), (138) and (140) by substituting eqns. (141)–(150) gives

$$v_{A12} + v_{B23} + v_{C3} = -\frac{Z_L}{Z_{12}} v_{A12} \quad . \quad . \quad . \quad (151)$$

$$\left(1 + \frac{Z_L}{Z_{12}}\right) v_{A12} + v_{B23} + v_{C3} = 0 \quad . \quad . \quad (152)$$

$$\frac{v_{B12}}{Z_{12}} - \frac{v'_{B12}}{Z_{12}} = \frac{v_{B23}}{Z_{23}} - \frac{v_{A12}}{Z_{12}} \quad . \quad . \quad . \quad . \quad (153)$$

$$\frac{v_{C23}}{Z_{23}} - \frac{v_{B12}}{Z_{12}} - \frac{v'_{C23}}{Z_{23}} + \frac{v'_{B12}}{Z_{12}} = \frac{v_{C3}}{Z_3} - \frac{v_{B23}}{Z_{23}} \quad . \quad . \quad (154)$$

$$\frac{v_{D3}}{Z_3} - \frac{v_{C23}}{Z_{23}} - \frac{v'_{D3}}{Z_3} + \frac{v'_{C23}}{Z_{23}} = \frac{v_{Dn}}{Z_n} \quad . \quad . \quad . \quad (155)$$

Substituting for the reverse voltages from eqns. (135), (137) and (139),

$$\frac{v_{B12}}{Z_{12}} - \frac{v_{B23} - v_{B12}}{Z_{12}} = \frac{v_{B23}}{Z_{23}} - \frac{v_{A12}}{Z_{12}} \quad . \quad . \quad (156)$$

$$\frac{v_{C23}}{Z_{23}} - \frac{v_{B12}}{Z_{12}} - \frac{v_{C3} - v_{C23} - v_{Dn}}{Z_{23}} + \frac{v_{B23} - v_{B12}}{Z_{12}} = \frac{v_{C3}}{Z_3} - \frac{v_{B23}}{Z_{23}} \quad . \quad (157)$$

and

$$\frac{v_{D3}}{Z_3} - \frac{v_{C23}}{Z_{23}} - \frac{v_{Dn} - v_{D3}}{Z_3} + \frac{v_{C3} - v_{C23} - v_{Dn}}{Z_{23}} = \frac{v_{Dn}}{Z_n} \quad . \quad (158)$$

Collecting terms,

$$\frac{2v_{B12}}{Z_{12}} - v_{B23}\left(\frac{1}{Z_{12}} + \frac{1}{Z_{23}}\right) + \frac{v_{A12}}{Z_{12}} = 0 \quad . \quad . \quad (159)$$

$$\frac{2v_{C23}}{Z_{23}} - \frac{2v_{B12}}{Z_{12}} - v_{C3}\left(\frac{1}{Z_{23}} + \frac{1}{Z_3}\right) + \frac{v_{Dn}}{Z_{23}} + v_{B23}\left(\frac{1}{Z_{12}} + \frac{1}{Z_{23}}\right) = \quad . \quad . \quad . \quad . \quad (160)$$

$$\frac{2v_{D3}}{Z_3} - \frac{2v_{C23}}{Z_{23}} - v_{Dn}\left(\frac{1}{Z_3} + \frac{1}{Z_{23}} + \frac{1}{Z_n}\right) + \frac{v_{C3}}{Z_{23}} = 0 \quad . \quad (161)$$

From eqn (161),

$$v_{Dn}\left(\frac{Z_{23}Z_3 + Z_{23}Z_n + Z_3 Z_n}{Z_{23}Z_3 Z_n}\right) = \frac{2v_{D3}}{Z_3} + \frac{v_{C3}}{Z_{23}} - \frac{2v_{C23}}{Z_{23}} \quad . \quad (162)$$

Substituting this in eqn. (160),

$$\frac{2v_{C23}}{Z_{23}} - \frac{2v_{B12}}{Z_{12}} - v_{C3}\left(\frac{1}{Z_{23}} + \frac{1}{Z_3}\right) + \left(\frac{Z_3 Z_n}{Z_{23}Z_3 + Z_{23}Z_n + Z_3 Z_n}\right)\left(\frac{2v_{D3}}{Z_3} + \frac{v_{C3}}{Z_{23}} - \frac{2v_{C23}}{Z_{23}}\right) + v_{B23}\left(\frac{1}{Z_{12}} + \frac{1}{Z_{23}}\right) = 0 \quad . \quad (163)$$

$$2v_{C23}\left[\frac{Z_3 + Z_n}{Z_{23}(Z_3 + Z_n) + Z_3 Z_n}\right] - \frac{2v_{B12}}{Z_{12}} + v_{B23}\left(\frac{Z_{12} + Z_{23}}{Z_{12}Z_{23}}\right) + 2v_{D3}\left[\frac{Z_n}{Z_{23}(Z_3 + Z_n) + Z_3 Z_n}\right] - v_{C3}\left[\frac{(Z_{23} + Z_3)(Z_3 + Z_n) + Z_3 Z_n}{[Z_{23}(Z_3 + Z_n) + Z_3 Z_n]Z_3}\right] = 0 \quad . \quad . \quad (164)$$

From eqns (152) and (159),

$$\frac{2v_{B12}}{Z_{12}} - v_{B23}\left(\frac{1}{Z_{12}} + \frac{1}{Z_{23}}\right) - \frac{1}{Z_{12}}\frac{Z_{12}}{Z_{12} + Z_L}(v_{B23} + v_{C3}) = 0 \quad . \quad (165)$$

$$v_{C3} = 2\frac{Z_{12} + Z_L}{Z_{12}} v_{B12} - \left[\frac{(Z_{12} + Z_L)(Z_{12} + Z_{23})}{Z_{12}Z_{23}} - 1\right] v_{B23} \quad . \quad . \quad . \quad . \quad (166)$$

Substituting this in eqn. (164) gives

$$2v_{C23}\left[\frac{Z_3 + Z_n}{Z_{23}(Z_3 + Z_n) + Z_3 Z_n}\right] - \frac{2v_{B12}}{Z_{12}} + v_{B23}\left(\frac{Z_{12} + Z_{23}}{Z_{12}Z_{23}}\right) + 2v_{D3}\left[\frac{Z_n}{Z_{23}(Z_3 + Z_n) + Z_3 Z_n)}\right]$$

$$- \left\{\frac{(Z_{23} + Z_3)(Z_3 + Z_n) + Z_3 Z_n}{Z_3[Z_{23}(Z_3 + Z_n) + Z_3 Z_n]}\right\} \times \left\{2v_{B12}\frac{Z_{12} + Z_L}{Z_{12}} - v_{B23}\left[\frac{(Z_{12} + Z_L)(Z_{12} + Z_{23})}{Z_{12}Z_{23}} - 1\right]\right\} = 0 \quad . \quad (167)$$

$$2v_{C23}\left[\frac{Z_3+Z_n}{Z_{23}(Z_3+Z_n)+Z_3Z_n}\right]-\frac{2v_{B12}}{Z_{12}}\left\{1+\frac{(Z_{23}+Z_3)(Z_3+Z_n)+Z_3Z_n}{[Z_{23}(Z_3+Z_n)+Z_3Z_n]}\times\frac{Z_{12}+Z_L}{Z_3}\right\}$$
$$+\frac{v_{B23}}{Z_{12}Z_{23}}\left\{Z_{12}+Z_{23}+[(Z_{12}+Z_L)(Z_{12}+Z_{23})-Z_{12}Z_{23}]\times\left[\frac{(Z_{23}+Z_3)(Z_3+Z_n)+Z_3Z_n}{Z_3[Z_{23}(Z_3+Z_n)+Z_3Z_n]}\right]\right\}+2v_{D3}\left[\frac{Z_n}{Z_{23}(Z_3+Z_n)+Z_3Z_n}\right]=0 \quad (168)$$

This gives v_{B23} in terms of the known incoming voltages v_{B12}, v_{C23} and v_{D3}. The solution may then be substituted in eqn. (167) to obtain v_{C3}, and these solutions inserted in eqn. (159) give v_{A12}. It will be noted that each of the outgoing waves has a component derived from all three of the incoming waves v_{B12}, v_{C23} and v_{D3}. Similar solutions may be obtained for the reflected wave V_{line}, v'_{B12}, v'_{C23}, v'_{D3}. Since each incoming wave produces a component in all the outgoing waves it will be seen that the network of reflections soon becomes extremely complex, especially since only rarely will two reflections occur at the same time. A similar series of formulae may be derived for waves approaching the links from the neutral side.

(9.7) Alternator with Unwound Bull Conductors at the beginning of the Winding: Initial Voltage Distribution and Surge Impedance

The winding in this case is assumed to consist of 3-core conductors with the bull conductors of the bars nearest the line terminal (A) left unconnected, i.e. the line terminal is connected to a bar some distance from the bull–inner and inner–outer links, as in the machine used for the impulse-voltage distribution tests. This is shown in Fig. 8, which represents a development of the winding and shows the travelling waves set up by an incoming surge.

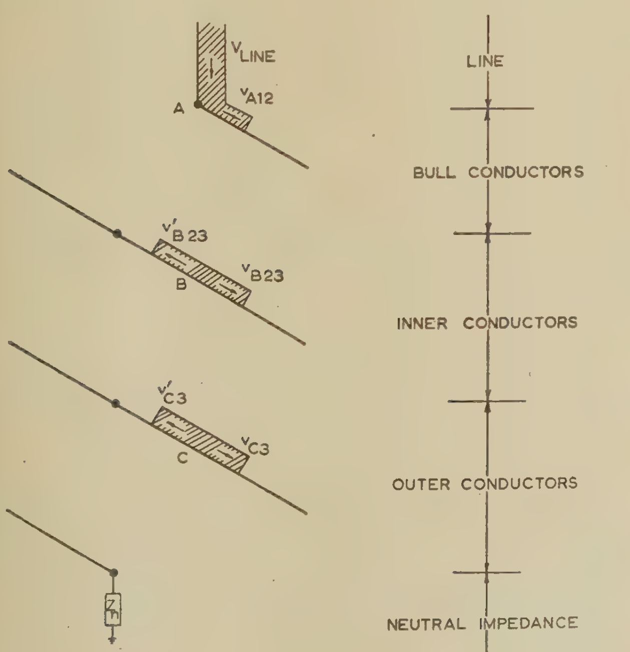


Fig. 8.—Diagram showing voltages induced by incoming surge V_{line} in winding having unwound bull conductors.

The equations for the propagation of the surge will be

$$v_{A12}=Z_{12}I_{A1} \quad (169)$$
$$v_{B23}=Z_{23}(I_{A1}+I_{B2}) \quad (170)$$
$$v_{C3}=Z_3(I_{A1}+I_{B2}+I_{C3}) \quad (171)$$
$$v'_{B23}=Z_{23}I'_{B2} \quad (172)$$
$$v'_{C3}=Z_3(I'_{B2}+I'_{C3}) \quad (173)$$
$$V_{line}=v_{A12}+v_{B23}+v_{C3} \quad (174)$$
$$v'_{B23}=v_{B23} \quad (175)$$
$$v'_{C3}=v_{C3} \quad (176)$$
$$I_{line}=I_{A1} \quad (177)$$
$$I'_{B2}+I_{B2}=0 \quad (178)$$
$$I'_{C3}+I_{C3}=0 \quad (179)$$

Substitute eqns. (178) and (179), (175) and (176) in eqns. (172) and (173):

$$v_{B23}=-Z_{23}I_{B2} \quad (180)$$
$$v_{C3}=-Z_3(I_{B2}+I_{C3}) \quad (181)$$

Combining eqns. (171) and (181) and eqns. (180) and (170) gives

$$2v_{C3}=Z_3I_{A1} \quad (182)$$
$$2v_{B23}=Z_{23}I_{A1} \quad (183)$$

Combining eqns. (169), (182) and (183) gives

$$\frac{v_{B23}}{v_{A12}}=\frac{Z_{23}}{2Z_{12}} \quad (184)$$
$$\frac{v_{C3}}{v_{A12}}=\frac{Z_3}{2Z_{12}} \quad (185)$$

Substituting these in eqn. (174) gives

$$V_{line}=\left[1+\frac{1}{2Z_{12}}(Z_{23}+Z_3)\right]v_{A12} \quad (186)$$
$$\frac{v_{A12}}{V_{line}}=\frac{2Z_{12}}{2Z_{12}+Z_{23}+Z_3} \quad (187)$$

Substituting eqns. (169), (182) and (183) in eqn. (174) gives

$$V_{line}=(Z_{12}+\tfrac{1}{2}Z_{23}+\tfrac{1}{2}Z_3)I_{A1} \quad (188)$$

Now the surge impedance Z_W is given by

$$Z_W=\frac{V_{line}}{I_{A12}}=Z_{12}+\tfrac{1}{2}(Z_{23}+Z_3) \quad (189)$$

Equations for the reflection and refraction of the travelling waves at the links and at the points of the winding corresponding to the first wound bull conductor may be derived in a manner similar to that used for the fully wound machine.

[The discussion on the above paper will be found overleaf.]

DISCUSSION BEFORE THE SUPPLY SECTION, 22ND FEBRUARY, 1956

Mr. R. Davis: Alternators may be connected to an overhead line either directly or via a transformer; in both cases the alternator may be subjected to transient over-voltages of atmospheric origin. This fact has long been appreciated, and at a recent I.E.C. meeting the question of impulse tests on rotating machinery was raised. Before suitable tests can be prescribed, the magnitude and form of the transient voltages which can be transmitted to the alternator winding need to be determined, and the author has attempted this in Paper No. 1997; experiments are described in which the voltages transferred to the alternator when a known surge voltage is applied to the transformer are recorded, and an attempt is made to interpret the observations theoretically. Since the valuable experimental data were obtained by well-known techniques I shall restrict my examination to the theoretical treatment and aspects of the presentation.

My main criticism is of the theoretical treatment. Fig. 2 is assumed to be the lumped-circuit equivalent of Fig. 1, and the solution for the alternator voltage involves an equation of the third degree. All that can usefully be done with such an equation is to substitute suitable values for the different parameters and solve the equation. When this is done the final solution differs considerably from the experimental observations. Instead of drawing the conclusion that either the lumped representation of the circuit or the choice of parameters is wrong, the author proceeds to develop two so-called solutions which he calls the 'dead beat' and the 'oscillatory'. For the dead-beat solution he invokes an oscillatory component which gives a 100% overshoot, and in spite of the fact that such a component will give an approximately 100% 'undershoot' half a period later, he doubles all the voltages of the original solution, and quotes these in Fig. 9 as a calculated curve.

In spite of the invocation of an oscillatory component for his dead-beat solution, he then proceeds to the so-called oscillatory solution. Here the value of P in eqn. (6) is replaced by

$$\left(P - \frac{1}{CZ_1}\right)$$

Since, from eqn. (7),

$$P = \frac{Z_2}{L} + \frac{1}{CZ_1} - \beta$$

this is equivalent to making $1/CZ_1$ equal to zero. Since C represents the capacitance of the alternator winding it must be finite; therefore Z_1 is infinite. Z_1 appears in eqns. (5) and (8), but the author does not state whether he has used this value in these equations.

It would appear that, up to the present, the author has not provided a theoretical determination of the maximum voltage transferred to the alternator winding which improves on the value derived from simple considerations based on the known ratio of the transformer.

Dr. E. Friedlander: Paper No. 2018 is built largely on the lines of Reference 3. The author's main progress is due to his introduction of different wave velocities by expressing all surge impedances in terms of those due to the inter-conductor capacitances and wave velocities. This results in the same equation for the surge impedance and the same initial wave pattern but somewhat different numerical values. With the author's data it is found that the theoretical maximum stress of the bull insulation calculated earlier to be 83% is now reduced to 72%. However, these data rely on the correct derivation of wave velocities from the surge tests. Since the velocity differences are due to the presence of iron, it would be important to know the voltage which was used. The current due to an incident wave of, say, 100 kV amplitude will highly saturate the iron and may correspondingly give only very slight differences of wave velocities compared with those to be expected from measurements with a recurrent-surge oscillograph having a wave amplitude of not more than about 300 volts. There are other possible sources of error: the steepness of the applied wave is limited; the injection of the voltage at four bars from the junction point between conductors almost doubles the surge impedance, as may be seen from a comparison of numerical data inserted into eqns. (25) and (189). Has this been checked experimentally?

The complexity of equations to be solved for plotting a proper lattice diagram when different wave velocities are introduced has led the author to the suggestion of further approximating his calculations by assuming coincident arrival of the various waves at the junction points; this, however, leads straight back to equal wave velocities, i.e. to the conditions of the earlier investigation, the results of which were well confirmed by experiments on a 3-core cable. To-day it would perhaps seem preferable to solve this problem numerically by means of a digital computer.

Mr. L. W. James: Protection is not normally provided in this country against transferred surges, although these are occasionally blamed for insulation breakdowns on generators. Recent American papers suggest that protection is not really necessary, but American engineers still appear to fit it.

Transformers are usually placed near the generators, using short bare connections having low capacitance to earth for large machines. Would the author expect to find any electrostatic transfer under these conditions, and would connection to a 275 or 380 kV system alter the values appreciably? Is there anything about the design of the transformers used for these tests which would account for the lack of electrostatic transfer? The Americans are still concerned about this in recent papers on the subject.

Some time ago a number of winding failures occurred on generators earthed through voltage transformers, and surge-transfer tests showed that, with the transformer h.v. neutral earthed, earthing the generator neutral had little effect; but with the h.v. neutral open, earthing the generator reduced the transferred surge to about one-third of the unearthed value.

The voltage of 53·6 kV quoted in Section 7 appears to be rather high for a machine which has been operating for, say, 20 years, although it should be well within the capabilities of a new machine.

From Paper No. 2018 it is noted that the voltage between conductors can be as high as 50%. Would this account for some of the occasional failures which have occurred on end-connector joints, where it is difficult to provide adequate creepage distance when a machine gets dirty?

Fig. 3 indicates a maximum voltage of about 43% on the outer conductors, and Fig. 4 shows 51%, which seems to indicate that earthing the generator neutral has some value; however, the Conclusions state that earthing the neutral point does not appreciably affect the surge-voltage stress in the machine.

Mr. R. W. Flux: The number of assumptions and approximations in Paper No. 1997 are such that none of the methods proposed for determining the magnitude of a surge transferred through a transformer to the windings of an alternator can be considered as satisfactory for making the basic decision as to whether such a voltage will endanger the insulation of the alternator.

Since the big generator transformers are now becoming standardized, the most practical solution would be to carry out recurrent-surge-oscillograph tests on the generator transformer

on the manufacturers' test-bed. Presumably, if it is permissible to assume an equivalent circuit for the alternator for the purpose of making calculations, it is equally permissible to utilize such an equivalent network for the purpose of tests with a recurrent-surge oscillograph. The proposal at least has the advantage that one major component in the circuit—the transformer—forms part of the test arrangement and no assumptions have to be made regarding its characteristics. If it were found that a dangerous surge voltage was likely to appear at the alternator terminals, there would still be ample time to fit surge arresters to these terminals before the complete equipment was put into commission.

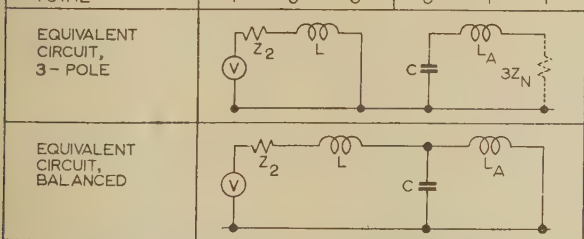
Mr. E. L. White: Experiment has not confirmed the forecast in Section 2.1.2 of Paper No. 1997 of the transference due to a 2-pole surge, and in Section 3.1 the results obtained with a 3-pole surge are attributed without explanation to leakage flux. Since it is clear that the mechanism has not been understood, the following analysis of the magnetic transference process may be of help.

Any system of surge voltages can be resolved,* by well-established principles, into two components, namely

(*a*) A 3-pole surge consisting of zero-sequence voltages of various frequencies.
(*b*) A balanced surge consisting of positive- and negative-sequence voltages, also of various frequencies, such that the sum of the phase voltages is always zero.

In a symmetrical circuit there is no interaction between these components, and each can be fully determined from consideration of a single-phase equivalent circuit. Fig. A shows the analysis

	SINGLE – POLE SURGE			TWO – POLE SURGE		
TERMINAL	A	B	C	A	B	C
3 – POLE COMPONENT	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
BALANCED COMPONENT	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
TOTAL	1	0	0	0	1	1



SURGE TRANSFERENCE THROUGH TRANSFORMER COUPLED TO AN ALTERNATOR

Fig. A.—Resolution into components and equivalent circuits of single-pole and 2-pole surges.

of single- and 2-pole surges into components, together with the equivalent circuit for each component. For symmetry, it is assumed that an impedance, Z_2, is present in each phase of the high-voltage connections. L and L_A are respectively the transformer leakage inductance and the alternator subtransient inductance, C is the effective capacitance of the cable and the alternator, Z_N is the neutral earthing impedance, and V is the appropriate component of the applied surge. All these are equivalent star values referred to the low-voltage side. From this Figure it can be seen that magnetic transference of voltage is zero for the 3-pole component, zero at the alternator neutral (whether the latter is earthed or not) and—as is confirmed experimentally by Figs. 9(*c*) and 9(*d*) of the paper—equal for single-and 2-pole surges (since the balanced components of these two are equal).

* Lacey, H. M.: 'Surge Phenomena' (E.R.A. Report Ref. S/T35: 1946, p. 118).

It is evident also that the transference resulting from a 3-pole surge must be due either to asymmetry of the circuit or capacitive transference, which could be distinguished from magnetic transference by the different frequency of oscillation excited by the transference.

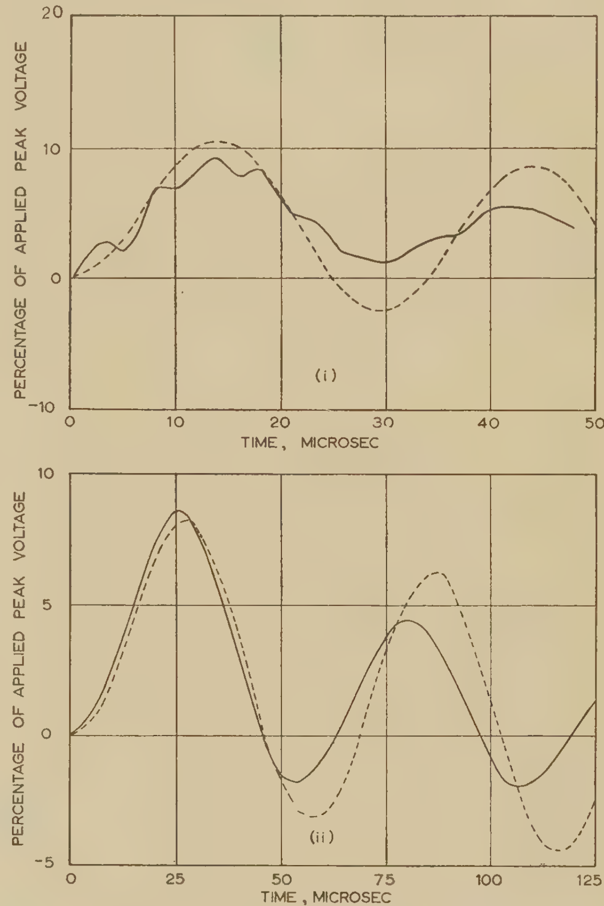


Fig. B.—Transference due to single-pole surge.

——— Measured.
– – – – Calculated.

(i) Oscillogram of Fig. 9(*a*) of the paper, and voltage computed from the circui in Fig. A.
(ii) Oscillogram of Fig. 9(*c*) of the paper, and voltage computed from the circuit in Fig. A.

Fig. B shows the oscillograms of Figs. 9(*a*) and 9(*c*) together with transference voltages computed from Fig. A, assuming $Z_2 = 0$. The agreement between theory and experiment is not worse than that obtained by the author.

Mr. J. A. S. Hilditch: I cannot accept the equivalent circuit used to represent the alternator in Paper No. 1997. Figs. 3 and 4 indicate that the surge impedance of the machine operates only for the first few microseconds, after which a substantially linear distribution of major voltage is dictated by the inductance of the windings. Each phase should therefore be represented by an equivalent lumped capacitance of one-third the total earth capacitance per phase shunted by its effective inductance (which appears to be the subtransient inductance), together with some resistance to simulate losses in the machine. This representation yields a terminal-voltage waveform which agrees closely with the oscillograms in Fig. 9.

It is easy to show that the alternator terminal voltage must have the same value for single- and 2-phase impulses. In Fig. C(i) the equivalent circuit, referred to the l.v. side, is reduced

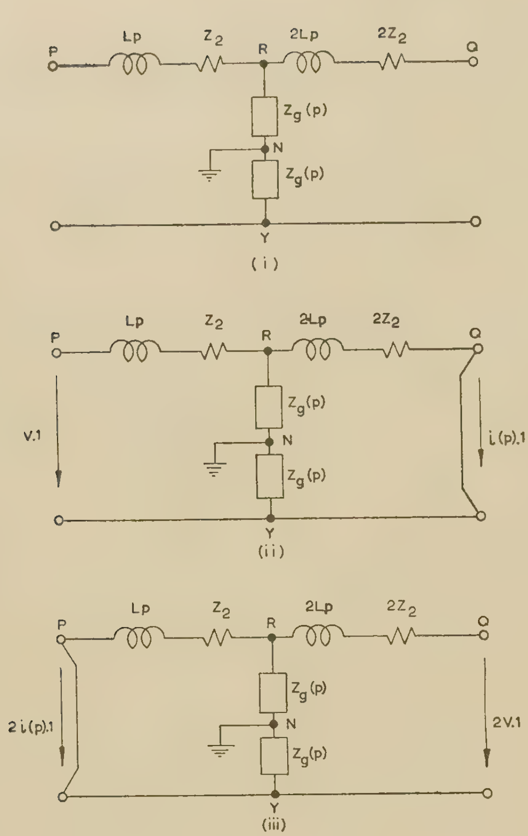


Fig. C.—Equivalent circuits.
(i) Equivalent T-network.
(ii) Single-phase impulse.
(iii) Two-phase impulse.

to a simple T-network, $Z_g(p)$ being the operational impedance of each alternator phase (by symmetry, one phase carries no current and is omitted). Fig. C(ii) shows the circuit for a single-phase impulse; here, a voltage $V1$ applied to terminals P–Y is assumed to cause current $i(p)1$ to flow through the short-circuit Q–Y. In Fig. C(iii), representing conditions for a 2-phase impulse, a voltage $2V1$ (derived from two delta windings in series) is applied to terminals Q–Y; owing to the reciprocal property of the network, current $2i(p)1$ must flow in the short-circuit P–Y. In both cases, the voltage to earth at terminal R or Y is the same and is equal to $(Lp + Z_2)i(p)1$.

This relation depends on the symmetrical loading of the transformer windings, by leakage inductance L and surge impedance Z_2 and not, as the author wrongly suggests, by the alternator; indeed, this may be removed without affecting the result. In the tests mentioned in Sections 3.1 and 3.2 Z_2 is considerably smaller than ωL, and thus its omission from the impulsed phases in Fig. 2 has a negligible effect.

Mr. D. H. Ryder: My remarks are concerned with the problem of surge voltages transferred through a transformer to an alternator. I have found that the magnetically transferred voltages can be evaluated by the turns-ratio method when the transformer is on open-circuit or is connected to an alternator. My experience has been almost entirely with the interleaved type of winding, but it is likely that most types of shielded windings have similar characteristics. The normal result of shielding the winding against surges is to produce as nearly as possible a linear distribution of voltage down the high-voltage winding. The ensuing current flow in the high-voltage winding also tends to be uniform down the winding, and with these conditions it has been found that the voltage magnetically transferred to the low-voltage winding is not complicated by travelling waves in the transformer, but is proportional to the turns ratio.

The actual value of the magnetically transferred voltage is dependent also upon the type of load existing at the low-voltage terminals. One element of this low-voltage load is shown correctly in Fig. 2 of the paper as the alternator capacitance C. The other element of the load should be represented as an inductance, rather than the surge impedance Z shown in the paper. Given the values of C and L in the low-voltage load, and knowing the transformer characteristics, the magnetically transferred voltage can be calculated.

The effects considered in the paper have been concerned with magnetically transferred voltages. I have found, however, that in some cases capacitance transfer of voltage cannot be ignored. When considering such cases the earthing of the neutral of the transformer or of the alternator is of great importance. In one combination of transformer and alternator the earthing of the neutral on the h.v. side of the transformer reduced voltages on the alternator by more than 50%. It was concluded that either the transformer neutral or the alternator neutral, or both, should be earthed through suitable impedances if it is desired to reduce the surges on the l.v. side to a minimum.

Mr. H. M. Lacey: Many references have been made to the transference of surge voltages in transformers, but I can recall only one case in which transference of surges was the cause of serious trouble. In this particular case serious interference with war-time production was caused by the breakdown of low-voltage busbars, and investigation showed that the trouble was caused by surges on the high-voltage side.

The turns ratio of the transformers and the low-voltage current were both extremely high, and it was necessary to minimize inductance in the whole circuit. The transformers were of the shell type, and the requirement of low reactance necessitated a large number of l.v. and h.v. groups, so producing very high capacitance between windings.

Tests showed that the ratio of transference of surges was only about 10 : 1, as compared with a turns ratio of 150 : 1. Thus with equal factors of safety, a surge which was innocuous on the h.v. side could be very serious on the l.v. side. I regard this case as exceptional, and doubt whether transference of surges is often the cause of trouble.

Prof. M. G. Say: It appears to be assumed that surge transfer in transformers is magnetic. Reference is made in Section 2.1.1 of Paper No. 1997 to the path of flux in the limbs. How can such a flux be established in a few microseconds, in view of the counter-effect of eddy currents? Any magnetic flux must be in leakage paths, and the transfer must differ markedly from normal-frequency transfer settled by the turns ratio. There must also be considerable transfer by capacitance.

In Section 4.2 of Paper No. 2018 the surge velocity is estimated in bars per microsecond, the fastest travel being 16 bars/microsec —a figure accurate to 1 part in 16. Yet the derived inductance is given to 1 part in 800—a quite unwarranted 'accuracy'.

There is no object in multiplying out the determinant in eqn. (48) when by an unavoidable simplification it is reduced to eqn. (50). In any case, the determinant is much more easily read than a very long equation. The same criticism applies in several places.

The capacitance C_t, which has to be neglected, is not well defined. It is presumably an overhang capacitance, because the slot bars are shielded from each other. There are so many discontinuities of the form C_t that, not only must additional reflections occur, but also couplings that distribute a terminal surge over several bar-ends at once. This may account for some of the inconsistency between analysis and experiment.

Mr. L. Csuros: The investigations reported in Paper No. 199

represent an important step towards clarifying a practical problem. The author's study seems to indicate that, with the arrangement of a transformer and generator adopted in this country in all modern generating stations, the surges transferred to the generator terminals do not reach magnitudes which could be harmful to machines whose insulation is up to modern standards. Furthermore, it appears that if surge diverters on the high-voltage side of the transformer (where diverters with a reduced voltage rating can be used, owing to the effective earthing of the system) cannot provide adequate surge protection for the generator, it is unlikely that surge diverters connected to the generator would be more efficient unless they had special characteristics, which, in turn, might reduce their reliability.

In considering the practical aspects of transferred surges it appears to me that the author's assumptions are on the safe side. All generator transformers on the British Grid now being installed have lightning arresters connected to their 132 kV terminals. The magnitude of surges on the high-voltage side of the generator transformer would, in this case, be limited to approximately 80% of 550 kV; the duration of the surge could be comparable with values assumed in the paper. Generator transformers of older construction are protected with co-ordinating gaps which have a flashover value of the order of 400–450 kV. Owing to the time lag, the surge voltage may reach 550 kV for a few microseconds, but as soon as the gap flashes over the voltage collapses; thus the duration of the surge will be considerably shorter than that assumed by the author. It therefore appears that, under practical conditions on the British Grid, either the magnitude or the duration of the surges applied to the transformer will, in general, be lower than those assumed in the paper. These factors would tend to reduce the magnitude of the surge transferred to the generator.

Mr. P. G. Ross: In Reference 9 of Paper No. 2018 Dr. Lewis criticizes certain aspects of the author's theory and claims that the low-frequency components of the applied steep-fronted wave are not propagated through the network representing the winding if account is taken of the network response itself. This criticism refers to an earlier paper by the author, but the theoretical treatment is similar to that in the present paper. Will the author comment on this criticism?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Dr. B. C. Robinson (*in reply*): From the commencement it was recognized that the mathematical treatment of the penetration of a surge through a transformer-alternator unit presented a difficult problem which could be solved only by approximations. Previous attempts had neglected to include the influence of the wavetail duration, which, as shown in Figs. 9(*e*)–9(*h*), produces a considerable effect on the transferred voltages. Moreover, those workers who had attempted a theoretical treatment had used a symmetrical circuit, and in my opinion it is wrong to include an impedance Z_2 between the applied voltage and the terminal of the transformer when in the tests the impulse was applied directly to the transformer terminal. Alternatively, it should not be omitted from the unimpulsed phases. These criticisms also appear to apply to some of the methods proposed in the discussion.

Referring to Mr. Davis's criticism of the methods used for the 'dead-beat solution', the solution to the operational equation was regarded as giving the maximum amplitude of the oscillations. It was also recognized that any solution must conform to the initial conditions $i = 0$ and $di/dt = 0$, where i is the current in the alternator winding. Thus the oscillations cannot take place about the zero line, but must occur about a voltage approximately equal to their amplitude; hence the doubling of the calculated value. Regarding the 'oscillatory solution', Mr. Davis has taken the approximations (5) and (7) too literally and as such has obtained an absurd result. Eqn. (5) gives an approximate value for the factor β and thus discriminates from the other factors. It is necessary to evaluate β accurately. The approximate value of P suggested the subtraction of the term $1/cZ_1$ to remove the excessive damping of the system by the other two factors. The true value of P, and not the approximate value given in eqn. (7), was used in the calculations.

I agree with Mr. Flux's suggestion that the difficulty of obtaining a transformer and alternator might be overcome by the use of an equivalent circuit for the alternator. I would prefer one using a large number of LC elements, say one for each coil in the machine, rather than the ones suggested in the paper. The simple LC circuit mentioned in the discussion may be satisfactory.

The possibility of electrostatic voltage transfer through the transformer, mentioned by Mr. James, will depend on the relative equivalent capacitances of the transformer (h.v. to l.v. windings) and of the alternator. For transformer X and alternator X the tests were carried out with overhead leads about 15 yd long connecting them, and as shown in Figs. 3–8, no appreciable electrostatic transfer was observed, owing to the alternator capacitance being much greater than that of the transformer. This latter had a standard disc-type winding as installed in some power stations in this country.

I thank Mr. Ryder and Mr. Hilditch for their suggestion of replacing Z_1 by an inductance equal to the alternator sub-transient inductance. It should, of course, be noted that, to obtain theoretical curves similar to the test results, it is necessary to use a reactance equal to the unsaturated sub-transient reactance, which is about 26% for alternator X and 40% for alternator YZ. This change in the representation of the alternator causes eqn. (3) for a single-phase impulse to become

$$p^3 + p^2\frac{Z_2}{L} + \frac{p}{C}\left(\frac{1}{L_A} + \frac{3k^2}{L}\right) + \frac{Z_2}{LC}\left(\frac{1}{L_A} + \frac{2k^2}{L}\right) \quad . \quad \text{(A)}$$

and eqn. (4), for a 2-phase impulse, to become

$$p^3 + \frac{Z_2}{L} + \frac{p}{C}\left(\frac{1}{L_A} + \frac{3k^2}{L}\right) + \frac{Z_2}{LC}\left(\frac{1}{L_A} + \frac{k^2}{L}\right) \quad . \quad \text{(B)}$$

where L_A is the alternator inductance. The inverse transforms of these are given by eqn. (2) when β, γ and ω are obtained as previously from eqns. (A) and (B). The corresponding values for Table 1 are given in Table A and appear to give better accuracy than those described in the paper.

I cannot see that the transferred voltages in an interleaved transformer, as mentioned by Mr. Ryder, will be different from

Table A

Fig. No.	Transformer	Number of phases impulsed	Maximum voltage to earth; percentage applied impulse	
			Test results	Calculated
9(*a*)	X	1	9·5	13·2
9(*b*)	X	2	11·6	12·0
9(*c*)	Y	1	8·6	7·9
9(*d*)	Y	2	8·9	7·7
9(*e*)	Z	1	34·4	35·1
9(*f*)	Z	2	36	33·2
9(*g*)	Z	1	41	42·8

those in other types, since the main voltage transfer is through the magnetic flux. His remarks regarding the effects of earthing the transformer neutral are interesting: all the tests given in the paper were done with the transformer neutral earthed, since it was considered that this would be a standard condition in a h.v. network especially for voltages of 132 kV and above.

It would seem that, in the arc-furnace transformer mentioned by Mr. Lacey, the transfer of voltage which caused the trouble was capacitive, not magnetic. The effective capacitance of the secondary side in this case would be relatively low compared with the transformer h.v./l.v. capacitance.

As Mr. Csuros says, the conditions assumed in Section 7 were probably pessimistic as regards the value of transferred surge obtained. It was, however, intended to give an approximate idea of the voltages obtained from eqn. (11).

Dr. Friedlander says that the principal innovation in the paper was the introduction of different wave velocities. He then suggests that the fact that many equations were derived for the simultaneous arrival of waves leads back to the use of equal wave velocities. This was not intended: the assumption of the simultaneous arrival of waves at the junction points was made to shorten the mathematics, since the effect of any single incoming wave could be readily obtained by equating the others to zero. Some idea of the errors likely to be introduced by assuming a constant velocity may be obtained from Fig. D, which shows the lattice diagram for the inter-conductor waves in an alternator during the first 5 microsec. In my opinion, any results obtained by assuming uniform velocities for the waves would be of little value.

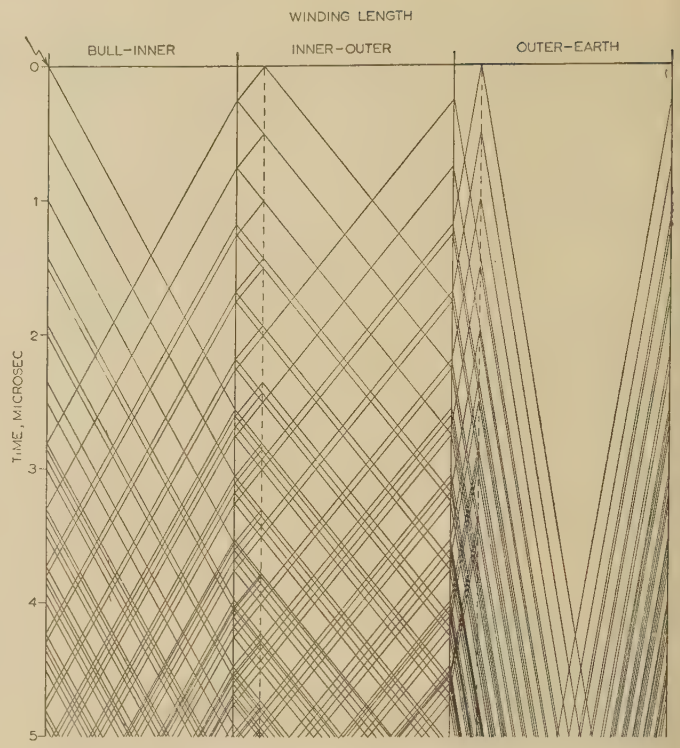


Fig. D.—Lattice diagram showing travelling waves in 3-core concentric-conductor alternator.

Regarding the effect of voltage on the voltage distribution, the tests were carried out with an applied impulse of 300–500 volts. Previously, however, tests had been made comparing the voltage distribution with applied voltages of about 1 and 50 kV, and no difference was detectable. The steepness of the applied impulse is governed by the critical frequency of the winding, as with a conventional winding. Despite the use of a low-impedance generator, it was found impossible to apply a very steep wave-front to the winding, owing to the low impedance of the winding to the super-critical frequencies in the applied wave.

Mr. James points out that 50% of the applied impulse may appear across a conductor bar joint and wonders whether surges might be the cause of occasional failures which occur on end-connection joints. While it is true that this means that the impulse flashover voltage of a machine is approximately equal to the insulation level of a 33 kV system, so far as our records show, no breakdowns have been attributed to this cause. Failures attributed to other causes are dealt with in a previous paper (Reference 5).

Mr. James also criticizes the statement that earthing the neutral does not appreciably affect the surge-voltage distribution, although it appears to reduce the maximum stress from 51 to 43%. While this is not negligible, the statement was intended to refer to the general behaviour of the winding and the types of stress produced. Comparison was also being made with the considerable modification of the behaviour and reduction in some of the stresses produced by earthing the neutral of a conventionally wound machine.

Mr. Ross asks for comments regarding certain remarks by Dr. Lewis in Reference 9. This is really a reference to the two theories of the penetration of surge voltages in windings. The standing-wave theory regards the winding as having a number of voltage (or current) oscillations in time and space. The application of the surge voltage upsets the initial equilibrium, and the resulting transient voltages take place until a new equilibrium is established. The travelling-wave theory regards the winding as being initially at rest, and the application of the surge voltage is really the application of a number of sinusoidal voltages. It can be proved that all the various sinusoidal voltages below a certain critical frequency can be considered to be propagated as travelling waves with velocities dependent on the winding parameters and their frequency. The resultant distribution is a sum of these sinusoidal voltages. Higher-frequency components are distributed through the winding by capacitance. Both theories are derived from the same differential equations and yield similar results.

621.316.925 : 621.313

Paper No. 2109 U
Aug. 1956

AN ELECTRONIC OVER-CURRENT RELAY FOR ELECTRICAL MACHINES

By J. S. H. GOODALL and G. S. CHAPMAN, Associate Members.

(*The paper was first received* 14*th December*, 1955, *and in revised form* 13*th March*, 1956.)

SUMMARY

The paper describes an electronic relay designed to protect electrical machines under over-current conditions. The advantages of this device over conventional thermal and magnetic protective relays are outlined, and methods of connection for single- and multi-phase working are discussed.

(1) INTRODUCTION

Over-current conditions in electrical machines, whether due to mechanical overload or electrical fault, will result in either a sharp rise of current to well above the machine rating or a gradual increase to perhaps a few per cent above the rating. The machine will also draw increased current during starting, the amount and duration of the increase depending on the method of starting and the load. The function of an overload protection device is to isolate the machine from the supply instantaneously if the current rises sharply (except during starting, when special provision is made) or after a predetermined duration of current above the machine rating at full load. Protection is normally afforded by thermal or magnetic overload relays, often incorporating a mechanical delay, but these devices have the following disadvantages:

(*a*) No indication is given of the type of magnitude of the overload which caused the relay to operate.
(*b*) Normal temperature changes may affect the operating conditions by altering the viscosity of the dashpot oil, etc.
(*c*) Repetitive starting cycles may cause a delayed-protection relay to operate as for an overload (a phenomenon known as 'creep').
(*d*) The complete device may have to be changed should the load conditions be changed materially.
(*e*) Accurate and consistent calibration is very difficult, especially with regard to delay times.
(*f*) No indication is given if the device itself fails, and testing it satisfactorily involves passing over-currents through the machine.

The electronic relay* described in the paper overcomes all the disadvantages, a single unit being adaptable for instantaneous or delayed operation, on either heavy transients or sustained slight overloads, by adjustment of variable components. In addition, it indicates incipient and actual overloads and the current flowing under these conditions, giving visual and aural warning; is suitable for remote operation and/or warning; is easily adaptable for single- or multi-phase working; and will isolate the machine from the supply should it develop a fault within itself. Although it employs thermionic valves—which power engineers tend to regard with suspicion—these are operated well below their rating and have yet to be responsible for a fault; however, provision is made to ensure that valve failure becomes apparent immediately and that the machine being protected is isolated from the supply.

Test points are provided so that, by applying suitable voltages from a dry battery, the relay may be tested with the load circuit inoperative.

* CHAPMAN, G. S., and GOODALL, J. S. H.: British Patent No. 734326.
GOODALL, J. S. H., and CHAPMAN, G. S.: British Patent No. 739413.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. Goodall and Mr. Chapman are at the Hastings and St. Leonards Technical College.

(2) DESCRIPTION OF RELAY

The relay consists of the following units:

(*a*) A power pack giving the high-voltage, standing-bias and heater supplies to the valves.
(*b*) Current-sensitive elements giving an output voltage proportional to the load current.
(*c*) A control thermionic valve and associated circuit to operate instantaneous relay circuits.
(*d*) A thermionic valve and circuit for providing delay operation.
(*e*) A diode and associated relay to give protection against failure of the high-voltage or valve-heater supplies within the device.
(*f*) A fluorescent current indicator.
(*g*) A visual and/or aural warning device to indicate instantaneous or delayed failure by overload.

A block schematic is shown in Fig. 1 and a full circuit diagram in Fig. 2. The latter shows the control device for operation on single-phase supply circuits; for multi-phase circuits it is only necessary to have a current-sensitive element in each phase and to connect the outputs in parallel to feed into the controller at FF. The contactor will, of course, have the appropriate number of switches similar to S_9 and S_{10}.

The controller is supplied from one phase on the live side of the contactor B. With the controller operating switch, S_8, open, the heaters of V_1–V_4 are energized through the transformer T_2. The heaters of V_1, V_3 and V_4 are connected in series; V_2 is the fluorescent indicator valve, its heater being in series with R_7 and connected to the output of transformer T_2. The grid-bias circuit is also energized when S_8 is open, the supply being from the secondary of T_2 via the rectifier X_4 and the smoothing network C_4, R_{10} and C_3. This bias is applied to the control grids of V_1 and V_2, biasing both valves to cut-off. With S_8 open, C_5 is charged from the mains supply by the rectifier X_3, via the contacts, S_2, of the relay L_2. The voltage across C_5 is applied between the control grid and the cathode of V_4, biasing the valve beyond cut-off. The warning light N_2 is energized to show that the controller is inoperative by the contacts S_4 of the relay L_3.

Closure of S_8 applies the h.v. supply to the controller via X_5 and the smoothing circuit C_7, T_3 and C_6. If the controller has no faults, V_3 conducts and relay L_3 becomes energized, closing the contacts S_4; this extinguishes N_2 and energizes the contactor coil L_5 via the contacts S_6 of relay L_4 in the 'break' position. V_1, V_2 and V_4 remain inoperative. N_3 is energized, indicating that the contactor B is closed, and the load is applied to the supply by switches S_9 and S_{10}. The contacts, S_5, of relay L_3 are used for aural and visual signalling as required.

When current is flowing in the load supply, a voltage is set up across the secondary of the current transformer T_1; if the load circuit is multi-phase or multi-wire, the voltage is set up across the series output of the transformers. The outputs from the current transformers at A are fed by the twin flexible leads, F, to the controller C, where the voltage is rectified by the voltage-doubler network X_1, X_2 and C_1, C_2, and the direct voltage proportional to the output from the current transformers at B appears across the resistors R_3 and R_4. R_3 is calibrated to show when the current flowing in the load wires is sufficient to energize V_1, i.e. when the voltage from the voltage-doubler network, which is

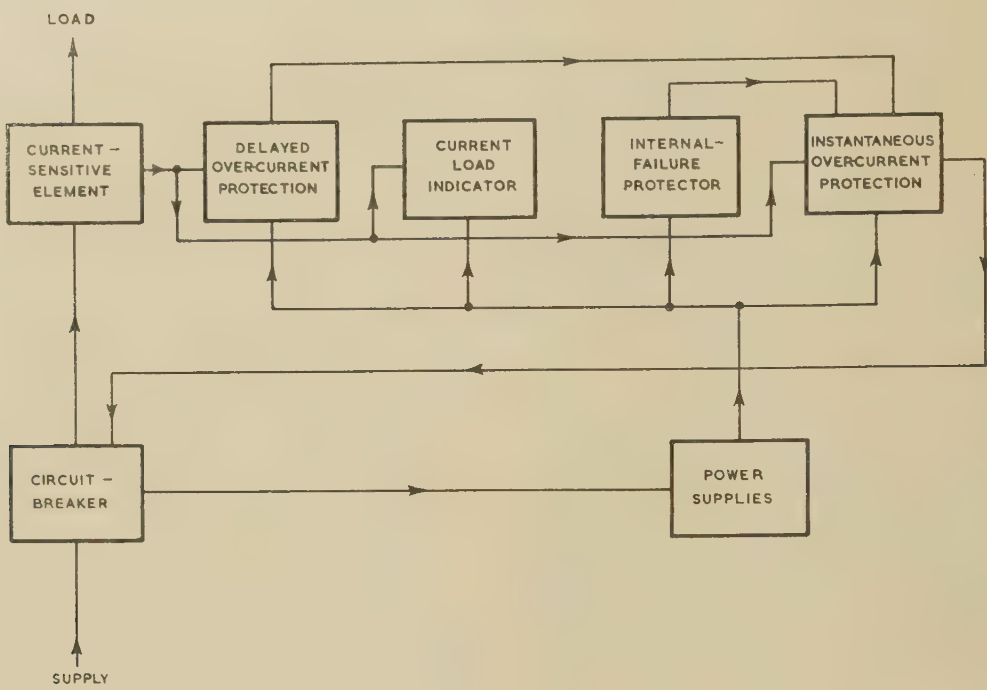


Fig. 1.—Block schematic of the electronic relay.

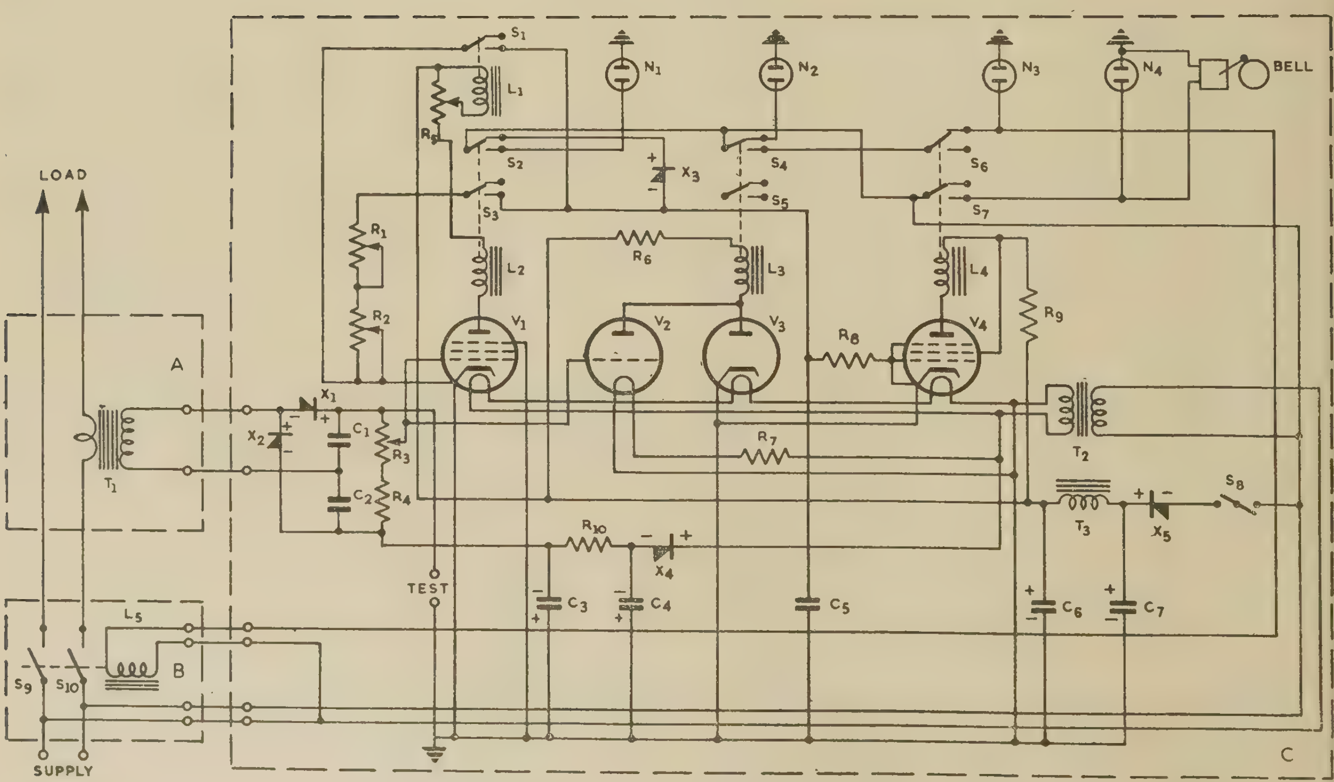


Fig. 2.—Circuit of the first experimental relay.

in opposition to the bias voltage, makes the control grid of V_1 sufficiently less negative with respect to the cathode for the valve to conduct. Hence R_3 is set to that current flowing in the load circuit which is considered to be an overload. When V_1 conducts—when the setting of R_3 is exceeded by the load taken from the supply—L_2 becomes energized, but L_1, which requires more current to energize it (owing to the potentiometer R_5), does not. Contacts S_2 and S_3 of L_2 then close, when the rectifier X_3 is isolated from the supply and C_5 ceases to be charged. Contacts S_2 energize the signal lamp N_1, indicating an overload. Contacts S_3 connect C_5 across the potentiometers R_1 and R_2, R_1 being graduated in minutes and R_2 in seconds. With both controls set at zero, C_5 discharges instantaneously.

The safe permissible duration of an overload is preset on the graduated scales of R_1 and R_2; if the overload clears within the preset time, V_1 ceases to conduct, L_2 becomes de-energized and S_2 and S_3 open, isolating C_5 from the discharge resistors R_1 and R_2 and connecting it to the charging rectifier X_3. V_4 hence remains at cut-off and the contactor coil L_5 remains energized. Should the overload persist beyond the preset time, C_5 discharges, V_4 conducts and L_4 closes. Contacts S_6 open-circuit the power supplies to N_3 and the contactor coil L_5; S_9 and S_{10} open and the load is isolated from the supply. At the same time, the warning indicator N_4 and the bell are energized. In the event of a heavy overload, the control grid of V_1 becomes positive and the current flowing through the anode circuit is sufficient to close relay L_1, the current required to do so being controlled by R_5. R_5 is calibrated (up to about 400%) to indicate the percentage of the current preset on R_3 which may pass before relay L_1 closes. When closed, contacts S_1 of L_1 cause C_5 to be discharged instantaneously, which causes V_4 to conduct, so de-energizing the contactor coil L_5 and isolating the supply.

V_2 is a subminiature indicator valve with fluorescent material coated on the anode. When the control-grid voltage is beyond cut-off there is no electron flow and hence the valve is dull. As the grid becomes less negative with respect to the heater, electron flow commences and the valve glows. Hence, when load current flows, V_2 glows, and the grid voltage is such that V_2 is glowing at maximum brilliance as the load current just approaches the overload value. The h.v. supply for V_2 is taken from the anode of V_3, which is at an appropriate voltage; since V_2 consumes about 0·1 mA it has no effect on the operation of V_3.

The controller may be remotely controlled by connecting a switch similar to S_8 in parallel with it. Remote warning lamps may be connected in parallel with N_1–N_4, and a remote bell may be connected in parallel with the controller bell.

Should any of the heaters of V_1, V_3 or V_4, or any of the supplies, fail, V_3 will become non-conductive and relay L_3 will be de-energized, causing contacts S_4 to open and cut off the supply to coil L_5 of contactor B: the supply will then be cut off from the load.

Later work with this type of controller has introduced certain simplifications. If the control grids of the valves are at a small positive potential or zero potential with respect to the cathode, driving them negative as the load current increases dispenses with the diode which acted as a safety device in the event of internal failure. This simplified circuit is shown in Fig. 3, which also indicates a 3-phase supply system.

No voltage-stabilizing circuits were included in the prototypes illustrated, and certain non-standard practices were adopted for simplicity, such as dispensing with a high-voltage transformer for power supplies in Fig. 2.

(3) CIRCUIT FOR APPARATUS REQUIRING LARGE STARTING CURRENTS

The circuit for large starting currents differs from that shown in Fig. 2 in two respects. First, V_1 and its associated circuits form the delayed overload protection; C_4, R_1, R_3 form the overload circuit, R_1 being calibrated in amperes; and R_2, R_1, R_3 and C_1, C_2 or C_3 form the exponential delay circuit. Secondly, V_2 and its associated circuits form the instantaneous overload protection. The voltage from the current-sensitive devices is fed

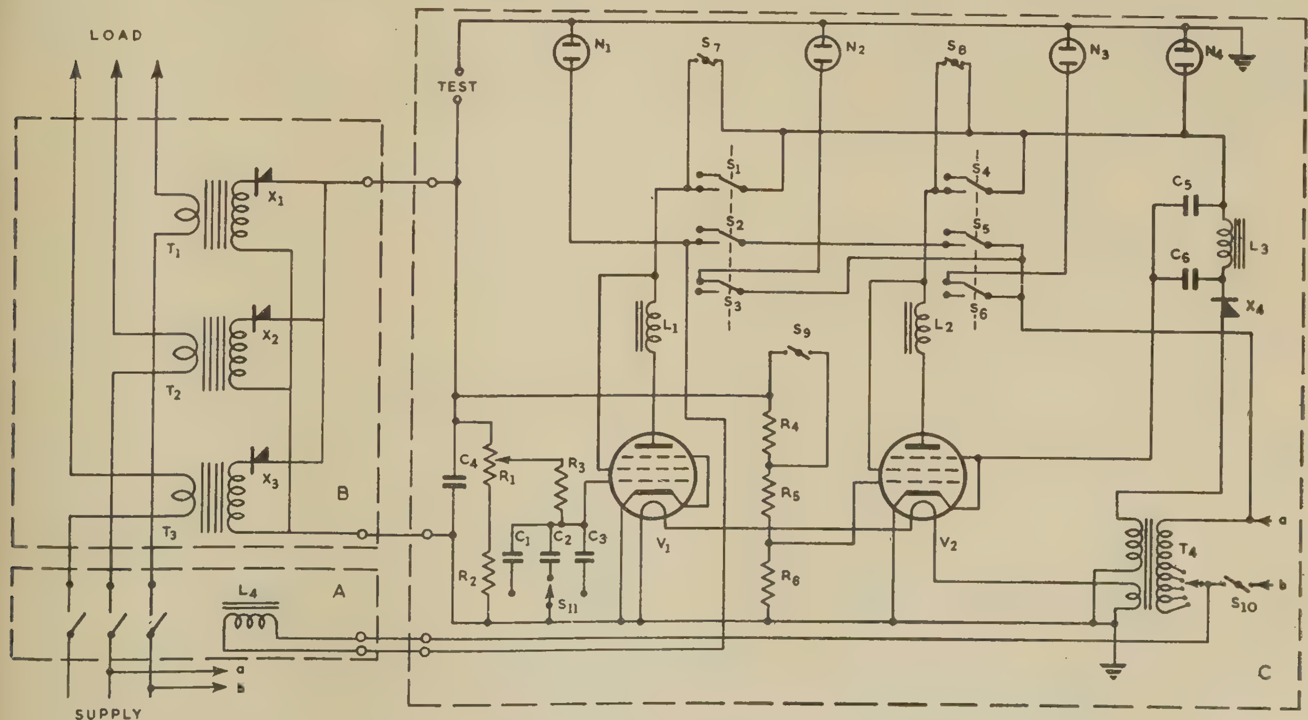


Fig. 3.—Circuit of the simplified relay.

across the potential divider R_4, R_5, R_6, and the voltage across R_6 is applied to the control grid of V_2. As the current consumed by the load increases, the control grid of V_2 goes more negative with respect to the cathode. When the device is used to protect motors and other apparatus consuming a starting current as much, as, say, 400% more than normal operating load, short-circuting R_4 by the pushbutton S_9 permits these heavy short-duration overloads to exist without the instantaneous relay tripping. When R_4 is reconnected the instantaneous release protection is again operative. In the prototype this operated at 150% of full load, although this figure may be varied to suit individual requirements by adjusting the ratio $R_6/(R_5 + R_4)$. To secure a variable instantaneous trip (as a percentage of the full-load current) a series of resistors and a Yaxley switch were arranged as shown in Fig. 4.

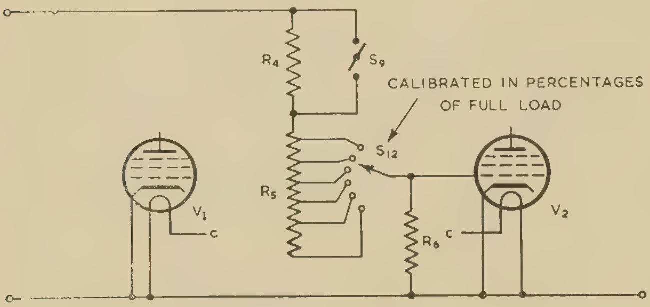


Fig. 4.—Circuit of variable instantaneous trip.

With this system, whereby the valves are constantly operative, reset pushbuttons S_7 and S_8 are required for each circuit. These are located near the appropriate neon indicator, i.e. S_7 near N_2 and S_8 near N_3, so that in the event of a small overload for a period greater than the delay period, as set on S_{11}, relay L_1 trips and indicator N_2 is energized, indicating that S_7 requires resetting when the cause of the overload has been cleared. In the event of a large overload exceeding the value set by the resistance network R_4–R_6, relay L_2 will trip N_3, indicating that resetting with pushbutton S_8 is necessary when the cause of the overload has been cleared.

A current-indicating device may be incorporated by taking a lead from the negative side of R_1 or C_4 to the control grid. Heater current may be obtained from transformer T_4 and the chassis via an appropriate resistor, while the anode voltage may be

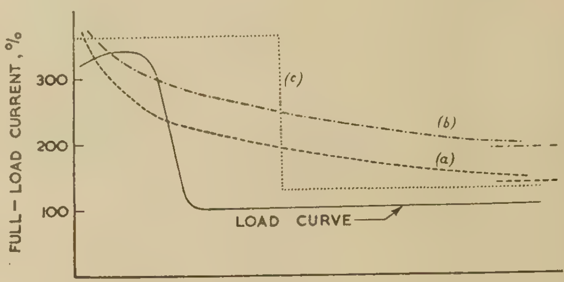


Fig. 5.—Load/time curves.

obtained from the h.v. supply through a suitable potential divider. This indicator will then operate conversely to that shown in Fig. 2, for extinguishing the fluorescent glow will indicate overload conditions.

(4) CONCLUSIONS

Figs. 2 and 3 show but two of a family of control devices which may be constructed, using the same basic concepts, for many varying uses, such as overspeed and underspeed protection, non-contact d.c. ammeters for heavy currents and other overload protection devices which would normally use thermal or magnetic switches.

To illustrate the advantages of the electronic relay, Fig. 5 shows load/time curves for a magnetic overload relay with an oil-dashpot delay incorporating a restraining device. Curve (*a*) shows that, if the overload trip is set to operate at 125% of full load, the relay does not give full protection and trips at the starting period. Setting the overload trip to 150% gives no true protection, as shown in curve (*b*). With the electronic relay, however, the instantaneous trip was adjusted to 350% of full load and the starter pushbutton was released after 6 sec; the protection characteristic obtained is shown in curve (*c*). In addition, the device incorporates a delayed-overload relay which operates after a preset current has flowed for a preset time.

621.316.925.45 : 621.314.7

Paper No. 2085 S
Aug. 1956

POWER SYSTEM PROTECTION, WITH PARTICULAR REFERENCE TO THE APPLICATION OF JUNCTION TRANSISTORS TO DISTANCE RELAYS

By COLIN ADAMSON, M.Sc.(Eng.), Associate Member, and L. M. WEDEPOHL, B.Sc.(Eng.), Graduate.

(*The paper was first received* 17*th December*, 1955, *and in revised form* 14*th February*, 1956.)

SUMMARY

The object of the paper is to describe early experience in designing and testing high-speed distance relays using junction transistors, and to expose the main difficulties in this field. The paper reviews briefly the history and application of electronic relays to electrical power-system protection and considers the general advantages of junction transistors over thermionic valves for this purpose. The principles of two distance relays using junction transistors are described, and it is shown that there is no theoretical difficulty in obtaining a range of relay characteristics within the general classification of 'distance relay', together with the properties of a straightforward directional relay. The particular susceptibility of the 'mho'-type distance relay and of the directional relay to collapse of line voltage is then discussed.

The circuits of the pulse type and direct phase comparison types of relay are described, together with the relay test arrangement and a brief exposition of the method of presenting the relay characteristics.

The operating characteristics of the relays, as expressed by accuracy/range curves, are explained, it being shown that the direct phase comparison type is more successful than the pulse type but that both are extremely susceptible to transient overreach; the nature of this latter phenomenon is discussed. It is concluded that junction transistors have some important operational advantages over thermionic valves where electronic protection can be justified, but that, in particular, the application of junction transistors, in common with conventional electronic circuits, to high-speed distance relays is dependent upon a satisfactory solution of the transient overreach problem; two possible ways of overcoming this latter difficulty are advocated. The rapid development of transistors is bringing their rating, power and length of life into a situation where it is thought they will be of importance in the design of new protective-gear relays and systems.

(1) HISTORY OF ELECTRONIC RELAYS

Proposals for electronic relays are not new, and references relating to their application to power system protection may be found in the literature from 1927 onwards. In that year, Fitzgerald[1] published a paper describing a scheme for an electronic pilot relay system; this scheme was subsequently discarded because of cost and lack of reliability of the valves available at that time. Wideröe[2] described, in 1931, a series of electronic circuits for most of the common types of protective-gear relays, and more recently, Loving[3] published circuits for many common protective-gear functions. Macpherson, Warrington and McConnell[4] described the situation up to 1948 and, in the same paper, gave information about an electronic 'mho' relay; subsequently, field experience with this type of relay was recounted by Barnes and Macpherson.[5] Later, work on distance protection was described by Kennedy[6] and by Kennedy and Barnes.[7] An electronic relay, having inverse-time characteristics, was developed by Honey and Readman.[8] Other electronic protection relays were described by Dlouhy[9] and by Cahen and Chevallier.[10]

Whereas justification can readily be found for the research and development work leading to the relays above, none has found general application for power-system protection. In one field, however, electronic protection has been successfully applied on a wide scale; this is where carrier relaying has produced a solution to the difficult problem of comparing conditions at the ends of a long transmission system, where economically it was not possible by other means. The literature on this aspect of the subject is extensive, e.g. References 1, 11, 12 and 13. It is not the purpose of the paper to discuss carrier protection, but it is the authors' view that the heavy power supplies required at present, using thermionic valves, together with the increased confidence in junction transistors, will attract the attention of engineers to the desirability of building carrier equipment with transistors.

(2) APPLICATION OF ELECTRONIC RELAYS

The adequacy of existing methods is always a most important factor in technological research and development, and in this context it must be noticed that over 90% of existing protective-gear requirements are easily met with electromagnetic techniques. Thus the schemes in use depend on the characteristics of induction-disc or cup relays and relays of the moving-coil and moving-armature types. The immediate advantages to supply engineers from any new techniques must clearly be marginal unless, as in the case of carrier, the protection requirements could not otherwise be satisfied in an economic manner. There are, however, wider issues and considerations; apart from the possibility of obtaining better performance and characteristics, e.g. higher speed with greater accuracy and sensitivity in distance-relay applications, one may engage in research and development for the purpose of introducing more standardization in manufacture or providing for easier manufacture and a reduction in maintenance time. Thus a recent paper by Edgley and Hamilton[14] claimed test and constructional advantages for a range of transductor relays; it is the opinion of the authors that similar advantages may well attend the use of transistors, since relays have been devised with desirable characteristics which require only transistors and a few common circuit components.

The situation with regard to the application of electronic relays has been carefully considered and is summarized in a recent paper to the C.I.G.R.É.[15] For completeness, the conclusions of the paper are reproduced below:

Advantages.

(*a*) Low burden on current transformers and voltage transformers, since the operating power is from an auxiliary d.c. supply.

(*b*) Absence of mechanical inertia and 'bouncing' contacts.

(*c*) Very fast operation.

(*d*) Low maintenance, owing to the absence of moving parts.

Limitations.

(*e*) The provision of special power supplies for valve heaters.

(*f*) The provision of appreciable voltages for valve anodes and electrode bias.

(*g*) Greater problems arise in ensuring correct operation under transient conditions owing to the performance of current transformers and voltage transformers than with the electromagnetic counterparts.

Mr. Adamson is at the Power Systems Laboratory, Department of Electrical Engineering, Faculty of Technology, University of Manchester.
Mr. Wedepohl is with the Electricity Supply Commission of South Africa, and is at present at the Power Systems Laboratory, University of Manchester.

It has also been reported that what had previously been a disadvantage, namely the limited output necessitating an electromagnetic relay for circuit-breaker trip-coil operation, had been overcome by the direct use of a thyratron which could handle 30 amp at 250 volts for 250 millisec.

The general conclusion arising from the points mentioned is that there are, at present, certain specialized applications for which electronic relays are suitable and have advantages over electromagnetic types. The margin of advantage is small, but as the limitations are overcome, it may be expected that the scope of application will widen.

(3) ADVANTAGES OF JUNCTION TRANSISTORS IN ELECTRONIC RELAYS

The junction transistor is a three-terminal, semi-conductor device, the three terminals being called the collector, emitter and base. Provided that the transistor is considered as a current-operated device, these three terminals have functions similar to the anode, grid and cathode, respectively, of a pentode valve. Transistors may be used in a number of different arrangements in electrical circuits; when used as a two-terminal network, there are three particularly useful configurations as indicated in Fig. 1(*a*).

(i) *Earthed collector.*—The collector is common, the input is between base and collector and the output between emitter and collector.
(ii) *Earthed base.*—The input is between emitter and base and the output is between collector and base.
(iii) *Earthed emitter.*—The input is between base and emitter and the output is between collector and emitter.

For large inputs the earthed-emitter arrangement behaves as a relay in which a small input power effects a change from a very high to a very low resistance in the output circuit.

(3.1) Earthed-Emitter Characteristics of a Junction Transistor

Fig. 1(*b*) shows the circuit arrangement, and Fig. 1(*c*) shows the static characteristic curves for the earthed-emitter configuration.

A load line AB is drawn on the characteristic, having slope $-1/R_A$ and intersecting the V_{ce}-axis at $-V_e$ volts. If the input resistance, R_b, is made large with respect to the base-emitter impedance, r_b, of the transistor (usually of the order of 400–700 ohms), the base current, to a first approximation, will be

$$I_b = \frac{V_{in}}{R_b}, \text{ when } V_{in} \text{ is negative.}$$

When V_{in} is positive, no base current will flow and the transistor will be cut off, so that the output voltage will be constant at V_0. When V_{in} becomes negative, base current starts to flow and the output potential falls along the load line until the point C is reached. At this point no further reduction in output voltage can occur, the only effect being an increase in the base current.

It is convenient to introduce α'', the large-signal amplification factor, or the ratio of emitter current to base current at the point C:

$$\alpha'' = I''_c/I''_b = \frac{2\,\text{mA}}{40\,\mu\text{A}} = 50 \text{ [in Fig. 1(}c\text{)]}$$

At the point C the output potential is so small that, to a first approximation, it can be assumed to be zero. Therefore, at that point,

$$I''_c = \frac{V_e}{R_A}$$

$$I''_b = \frac{V_e}{\alpha'' R_A}$$

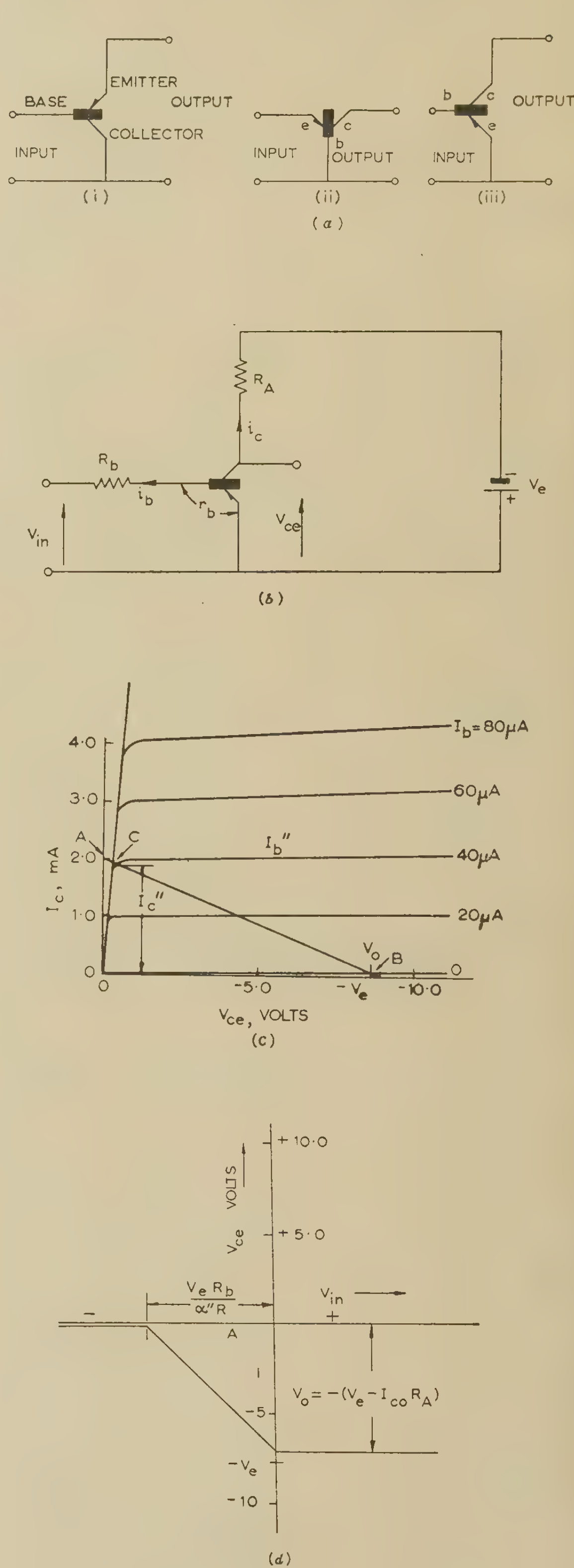


Fig. 1.—Transistor circuits and characteristics.

(*a*) Basic transistor configurations.
(i) Earthed collector.
(ii) Earthed base.
(iii) Earthed emitter.
(*b*) Basic transistor amplifier.
(*c*) Earthed-emitter characteristic curves.
(*d*) Switching characteristic of junction transistor.

and
$$V_{in} = I_b'' R_b$$
$$= \frac{V_e R_b}{\alpha'' R_A}$$

Thus the behaviour of this circuit may be summarized as follows:

For $V_{in} \geqslant 0, \quad V_{ce} = V_0 = -(V_e - I_{c0} R_A)$

For $V_{in} \leqslant -\frac{V_e R_b}{\alpha'' R_A}, \quad V_{ce} = 0$

The overall characteristic will be as in Fig. 1(*d*).

The transition from the cut-off to the fully-conducting condition takes place for a very small change of input voltage. Typical figures are as follows:

$$V_e = 10 \text{ volts}$$
$$R_b = 10\,000 \text{ ohms}$$
$$R_A = 20\,000 \text{ ohms}$$
$$\alpha'' = 30$$

Therefore $\frac{-V_e R_b}{\alpha'' R_A} = -0{\cdot}17$ volts

Thus, to a first approximation, the circuit behaves as a switch; it is in the 'off' condition for positive inputs, and vice versa for the 'on' condition. This argument holds only for large-signal conditions; the assumption is justified for the relay circuits which have been developed, since the input voltages were taken directly from the 110-volt test-transformer secondary windings.

(3.2) Application of Junction Transistors

It is obvious that, if the junction transistor can be applied to protective-gear relays in place of thermionic valves, limitation (*e*) of Section 2.2 is removed, and that a big step has been made towards eliminating (*f*), since h.t. voltages in excess of 10 volts are not required. Since their inception a few years ago, junction transistors have been very widely applied, and as a result their cost has started to fall and confidence in their reliability and in the stability of their characteristics has grown. In physical size they are small—sufficiently small in fact to make capacitors the circuit elements limiting the final size of any complete transistor relay. Experimental transistors are now available in ratings up to 2 watts; their efficiency and high current gain from base to collector make for low burdens on current transformers and voltage transformers.

Having reached this stage of development and availability, it was obvious that thought could be given to the application of junction transistors, and accordingly a project was started in the Power Systems Laboratory of the College of Technology, Manchester. The paper describes the first results of the work and deals with two relays in the most obvious application, namely to high-speed distance protection. These relays, their development, their characteristics and their limitations are described in full in the paper to follow. It was intended that the maximum experience should be gained with these relays, and to this end they were tested under exacting conditions on a modern protective-gear test bench.

(4) PRINCIPLE OF THE RELAYS

The relays make use of phase-comparison principles. These are general to electrical and electronic circuits and are not peculiar to transistors. They are briefly described in the following Sections.

(4.1) Pulse Type of Phase Comparator

The block diagram of the pulse type of relay is shown in Fig. 2(*a*). Line voltage and current are applied to two measuring circuits, which produce complex output voltages:

$$V_1 = k_1 V_L + Z_{R1} I_L$$
$$V_2 = k_2 V_L + Z_{R2} I_L, \text{ respectively,}$$

where k_1 and k_2 are usually real numbers representing transformer turns ratios, and Z_{R1} and Z_{R2} are transfer impedances.*

V_2 is applied to a pulsing circuit which produces a positive pulse once every cycle, when V_2 is at its positive maximum. V_1 and the pulse derived from V_2 are then applied to the terminals of a coincidence circuit of the type requiring both input terminals to become positive before producing any potential change at its output terminals. The criterion for relay operation is thus defined, since the coincidence circuit only yields an output when the pulse is present, and then only if V_1 is positive at this instant. If α is the phase angle between V_1 and V_2, it follows that $-90° < \alpha < +90°$ for V_1 to be positive at the instant of V_2 maximum.

(4.2) Direct Phase Comparator

The block diagram for the direct phase comparator is shown in Fig. 2(*b*). The two measuring circuits are, as before, producing the same two output voltages V_1 and V_2. In this case, however, both voltages are applied directly to the coincidence circuit, so that the output is a voltage block lasting for the duration of coincidence. This block is then applied to an integrating circuit and level detector, which determines whether the block is greater than 90 electrical degrees in duration, and, if so, produces a change in output voltage.

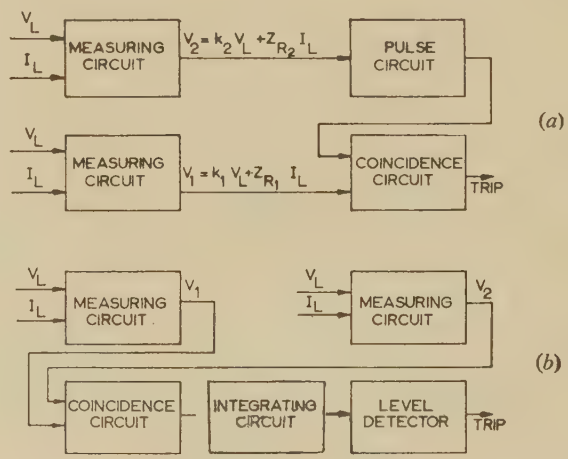


Fig. 2.—Block schematics of relays.

(*a*) Pulse relay.
(*b*) Direct-phase-comparison relay.

The criterion for operation is therefore that the duration of coincidence should be greater than 90 electrical degrees. This means that the phase angle between the two voltages, V_1 and V_2, should be less than 90°, which is the same condition as for the relay described in Section 4.1.

It may be noted that the phase-comparison principle involving pulse techniques was used originally by Wideröe[2] in his high-speed thyratron relays. The principle was used later in a more refined form by both Loving[3] and Macpherson, Warrington and

* These are frequently referred to as 'replica impedances' in American literature on protective gear.

McConnell.[4] The direct-phase-comparison principle has been described recently in two papers by Kennedy[6] and Kennedy and Barnes.[7]

(5) RELAY CHARACTERISTICS

With reference to Figs. 2(*a*) and 2(*b*), it is shown in Appendix 11.1 that the criterion for relay operation is

$$k_1k_2Z_L^2 + Z_L[k_1Z_{R2}\cos(\theta_2 - \phi_L) + k_2Z_{R1}\cos(\theta_1 - \phi_2)] + Z_{R1}Z_{R2}\cos(\theta_1 - \theta_2) > 0$$

From this general solution the properties of a number of particular relay types may be predicted.

(5.1) Alternative Relay Characteristics

(5.1.1) Directional Relay.

$$Z_{R1} = 0, \quad k_2 = 0$$

Therefore $\quad Z_Lk_1Z_{R2}\cos(\theta_2 - \phi_L) > 0$

i.e. $\quad \cos(\theta_2 - \phi_L) > 0$

and $\quad -\pi/2 + \theta_2 < \phi_L < \dfrac{\pi}{2} + \theta_2$

Operation occurs to the right of the straight line shown shaded in Fig. 3, and the slope of the line may be controlled by varying θ_2.

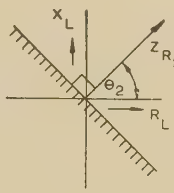


Fig. 3.—Directional relay characteristic.

(5.1.2) Ohm Relay.

$$k_1 = -k, \quad k_2 = 0$$

$$Z_{R1} = Z_{R2} = Z_R, \quad \theta_1 = \theta_2 = \theta$$

$$-Z_LkZ_R\cos(\theta - \phi_L) + Z_R^2 > 0$$

i.e. $\quad Z_L\cos(\theta - \phi_L) < Z_R/k$

This is the polar equation to the straight line shown in Fig. 4(*a*).

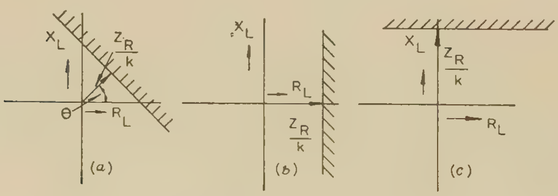


Fig. 4.—Relay characteristics.

(*a*) Ohm relay.
(*b*) Resistance relay.
(*c*) Reactance relay.

(5.1.2.1) *Resistance Relay.*

The resistance relay follows from the ohm relay, for the condition $\theta = 0$, when

$$Z_L\cos\phi_L < Z_R/k$$

i.e. $\quad R_L < Z_R/k$ [Fig. 4(*b*)]

(5.1.2.2) *Reactance Relay.*

The reactance relay also follows from the ohm relay, but fo the condition $\theta = \pi/2$, when

$$Z_L\sin\phi_L < Z_R/k$$

i.e. $\quad X_L < Z_R/k$ [Fig. 4(*c*)]

(5.1.3) Offset Impedance Relay.

$$k_1 = k, \quad k_2 = -k$$

$$\theta_1 = \theta_2 = \theta$$

$$-k^2Z_L^2 + kZ_LZ_{R2}\cos(\theta - \phi_L) - kZ_LZ_{R1}\cos(\theta - \phi_L) + Z_{R1}Z_{R2} >$$

This may be shown to be the equation to a circle of radiu $(Z_{R1} + Z_{R2})/2k$ and with centre $(Z_{R2} - Z_{R1})/2k\angle\theta$. This is show in Fig. 5(*a*).

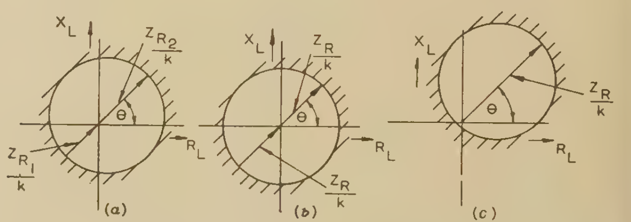


Fig. 5.—Relay characteristics.

(*a*) Offset impedance relay.
(*b*) Impedance relay.
(*c*) 'Mho' relay.

(5.1.3.1) *Impedance Relay.*

In the impedance relay $Z_{R2} = Z_{R1} = Z_R$, and the centre c the circle becomes the origin, the radius being Z_R/k, as in Fig. 5(*b*

(5.1.3.2) *Mho Relay.*

In the mho relay $Z_{R1} = 0$, $Z_{R2} = Z_R$, and the radius become $Z_R/2k$, the circumference of the circle passing through the origi as in Fig. 5(*c*). The particular properties of this important rela have been discussed in detail by numerous authors, e.g. Warring ton.[16,17] The authors of the present paper have concentrate their attention on relays with this type of characteristic.

(5.2) Special Properties of Directional and Mho Relays

Referring to the equation in Section 5 giving the gener criterion for operation of the relay, it should be noted that, either Z_{R1} or Z_{R2} is zero, indeterminacy results if $V_L =$ Considering the case of the directional relay,

$$Z_{R1} = 0, \quad k_2 = 0$$

Thus $\quad k_1V_LI_LZ_{R2}\cos(\theta_2 - \phi_L) > 0.$

It may be observed that collapse of V_L, i.e. for a nearby feed or busbar fault, renders this criterion indeterminate not on because $V_L \to 0$, but because ϕ_L can no longer be measured t the relay.

In the mho relay k_1V_L and $(Z_{R2}I_L - k_2V_L)$ are compared phase; the same condition as in the directional relay arises sinc when $V_L \to 0$, indeterminacy results.

Thus in both cases it is necessary to sustain k_1V_L for a sufficie time to enable both the directional and the mho relay to preser their correct directional properties. This is known as 'memo action'. In the above equations, for the mho relay only, k_1V_L usually referred to as the 'polarizing voltage' and k_2V_L as t 'restraint voltage'.

(5.3) The Impedance Z_R

The two transistor relays which were originally built and tested had 'mho' characteristics; the transfer impedance, Z_R, was obtained by using a transformer reactor with a resistance-loaded secondary winding. The equivalent circuit of the transformer reactor is shown in Fig. 6, and by the familiar analysis of this circuit, the transfer impedance is

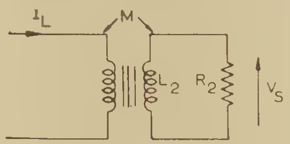


Fig. 6.—Equivalent circuit of transformer reactor.

$$Z_R = \frac{V_S}{I_L} = \frac{\omega M R_2}{\sqrt{(R_2^2 + \omega^2 L_2^2)}} \angle \underline{\pi/2 - \phi_2}$$

and
$$\tan \phi_2 = \omega L_2 / R_2$$

It is customary, but not essential, to make $(\pi/2 - \phi_2) = \phi_L$, the phase angle by which the line current lags behind the line voltage for a line short-circuit, in which case $\tan \phi_L = R_2/\omega L_2$.

(6) EXPLANATION OF THE CIRCUITS USED IN THE RELAY MODELS

(6.1) Conventions of Schematic

In Section 3.1, the use of the junction transistor as a switch has been briefly described. For the sake of simplicity, in the explanation to follow of the operation of the two relay models, the transistors have been shown schematically as switches. Thus, in Fig. 7(a) symbols b, c and e represent the base, collector

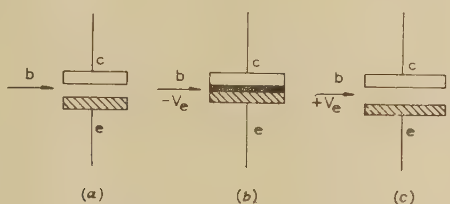


Fig. 7.—Schematics of transistors as switches.

and emitter, respectively, of a transistor, where b is the control electrode. When b is at a negative potential, the collector and emitter are short-circuited, as in Fig. 7(b); when b is at a positive potential, the collector and emitter are open-circuited as in Fig. 7(c).

(6.2) Pulse-type Relay

Fig. 8(a) is the schematic arrangement of the pulse-type relay. When V_1 changes from positive to negative, the transistor T_1 switches on and produces a negative pulse at the transformer output; the converse is also true, a positive pulse being produced when V_1 changes from negative to positive. A 90° phase shift is introduced, since, as indicated in Section 4.1, it is necessary to produce the switching pulse at the instant of maximum V_1 rather than at either of the instants when V_1 is passing through zero. In Fig. 8(a), T_2 and T_3 form the elements of a coincidence circuit as described in Section 4.1. A small negative bias, $-V_b$, on the bases of T_2 and T_3 ensures that these transistors are normally switched on and that the point a is at the common potential. It is thus necessary for V_2 to be positive at the instant of positive pulse for any output change to occur at the point a. If this condition is fulfilled, both transistors switch off simultaneously

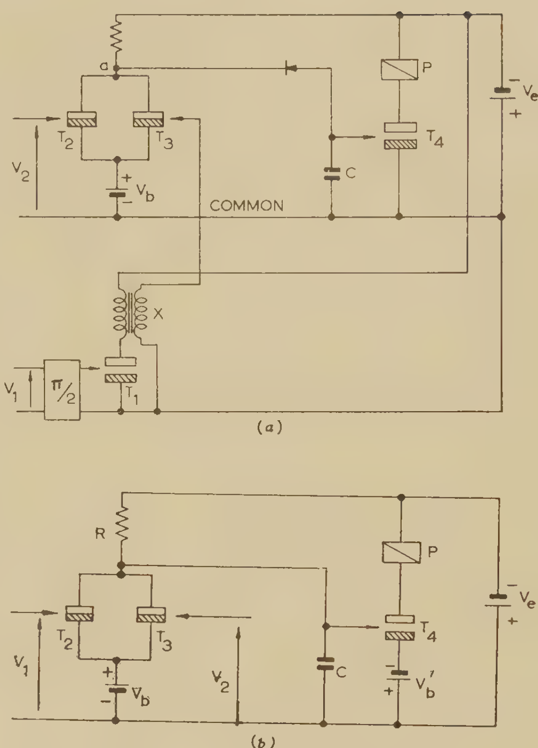


Fig. 8.—Schematics of relays.
(a) Pulse-type relay.
(b) Direct-phase-comparison relay.

and point a falls to $-V_e$ volts, charging C through the rectifier. The increase in negative voltage on C switches on the transistor T_4 and operates the telephone-type relay P. These circuit arrangements are sufficient to produce the relay characteristics of Section 5.1.

(6.3) Direct-phase-comparison Relay

The direct-phase-comparison relay is shown in Fig. 8(b); the coincidence circuit is as before, both transistors T_2 and T_3 being switched on. When T_2 and T_3 are switched off simultaneously, the capacitor C commences to charge according to the law

$$v_c = -V_e(1 - \varepsilon^{-t/CR})$$

CR is so arranged that when $t = 5$ millisec (0·25 cycle) $v_c = -V_b'$; thus the voltage on the condenser counteracts the effect of the bias V_b' on T_4, and T_4 switches on, causing operation of the relay P. As soon as either V_1 or V_2 becomes zero or negative, C discharges. It is thus necessary for V_1 and V_2 to be simultaneously positive for more than 90 electrical degrees; this corresponds to a phase displacement between V_1 and V_2 of less than 90° before operation can occur.

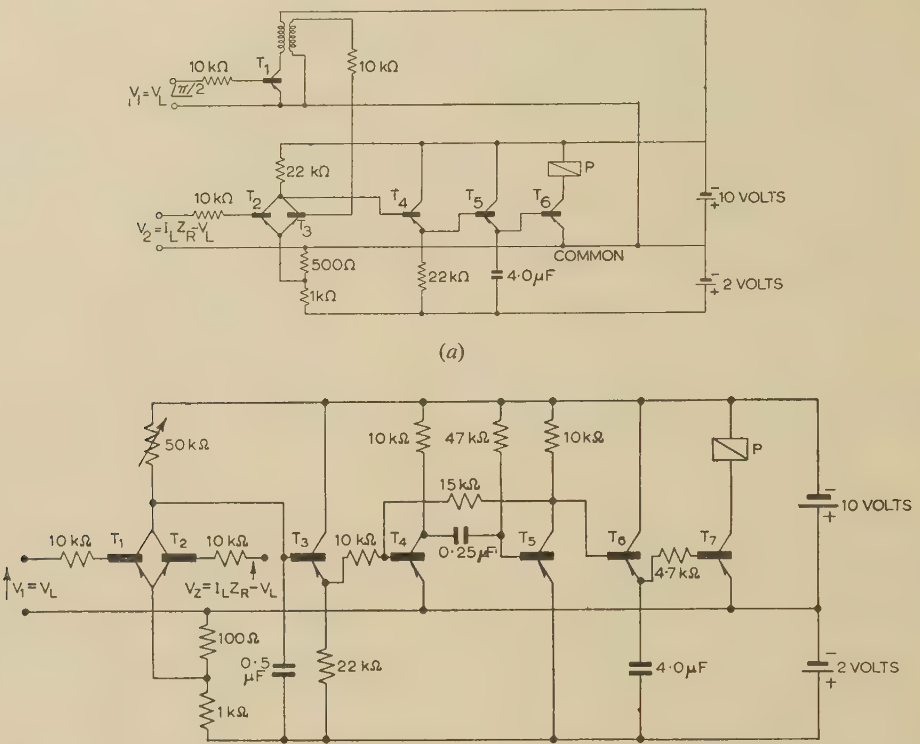
These circuit arrangements are again appropriate to the relay characteristics of Section 5.1.

(6.4) Complete Circuits

The complete circuits are shown in Figs. 9(a) and 9(b). The greater number of transistors shown in these circuits is due to the simplification introduced into the schematics [Figs. 8(a) and 8(b)].

(7) RELAY TESTING

The pulse and direct-phase-comparison types of relay were both arranged to have 'mho' characteristics in accordance with



(a)

(b)

Fig. 9.—Circuit diagrams of relays.

(a) Pulse-type relay.
(b) Direct-phase-comparison relay.

the criteria of Section 5.1.3.2, and were subjected to the same series of tests.

(7.1) Test Arrangements

Dynamic tests were carried out on a test bench* designed to simulate accurately the appropriate power-system conditions. This test bench, and the method of presentation of results mentioned in Section 7.2, were originated by Hamilton and Ellis.[18,19] It is equipped with supply voltages, source impedances, the line impedances for 3-phase working and with earth-fault impedance; by a suitable choice of fault selector switches any type of single or multiple fault may be simulated. A line diagram of one phase of the apparatus is shown in Fig. 10(a). S_1 is the main contactor and S_2 is a high-speed fault-closing switch. The bench was so arranged that S_1 closed first and S_2 could be made to close its contacts at any point in the voltage cycle by means of a point-on-wave control. The duration of the fault could also be controlled, before interruption of the fault by S_1.

Z_s could be varied in both magnitude and phase and had a maximum ratio of reactance to resistance of 50; Z_L could be varied in magnitude but had a fixed reactance/resistance ratio corresponding to mean values of a 132 kV line. The maximum and minimum fault currents available on the 1 amp secondary windings of the bench current transformers were 20 amp and approximately 0·05 amp, respectively. The phase-to-phase voltage on the secondary windings of the bench voltage transformers was 110 volts.

Only one relay was available in each case, and was connected for the first series of tests as a phase-fault relay, the connections being indicated in Fig. 10(b).

* The test bench and the method of presentation of results mentioned in Section 7.2 were originated by Messrs. F. L. Hamilton and N. S. Ellis.

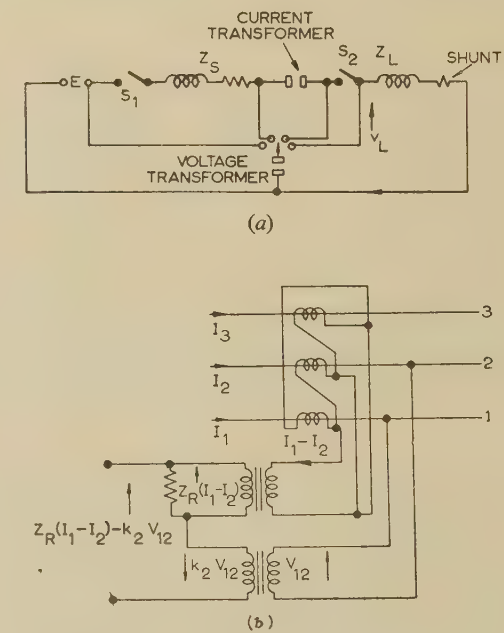


Fig. 10.—Relay test arrangements.

(a) Schematic of relay test bench.
(b) Test arrangements—phase fault relay.

For the second series of tests, the relay was again connected a[s] a phase-fault relay, but the polarizing voltage $k_1 V_L$ was derive[d] from the line-to-line source voltage; this simulates the derivatio[n] of voltage from the unfaulted phase in the case of a line-to-lin[e]

fault on an actual system. For test purposes, this overcomes the problem of polarizing-voltage collapse emphasized in Section 5.2.

Static 'mho' curves were obtained by the method of secondary injection in the usual way.

(7.2) Presentation of Relay Characteristics

The method of presentation of relay test results is in the form of accuracy/range curves, as in Figs. 11 and 12. The accuracy x is defined as the ratio Z_L/Z_R, and the threshold accuracy as the ratio

$$\frac{\text{Impedance just causing operation of relay}}{\text{Impedance setting of the relay, } Z_R}$$

Both quantities are referred to the relay input terminals.

The range y is defined as the ratio

$$y = \frac{\text{System source impedance}}{\text{Impedance setting of the relay}}$$

Both quantities are again referred to the relay input terminals. Ideally the relay should operate in a manner independent of external system conditions, i.e. it should not operate when $x > 1$ but should operate for $x \leqslant 1$. In practice, the source impedance affects the magnitude of the fault current, and this in turn impairs the accuracy of the relay.

(7.3) Dynamic Test Results

Figs. 11 and 12 show the accuracy/range curves for the pulse and direct-phase-comparison distance relays, respectively. Figs. 13 and 14 show a similar set of curves for the second series of tests, corresponding to the case of externally-derived polarizing voltage. All tests were taken for the case of zero-current transient for reasons which will be explained in Section 7.3.3.

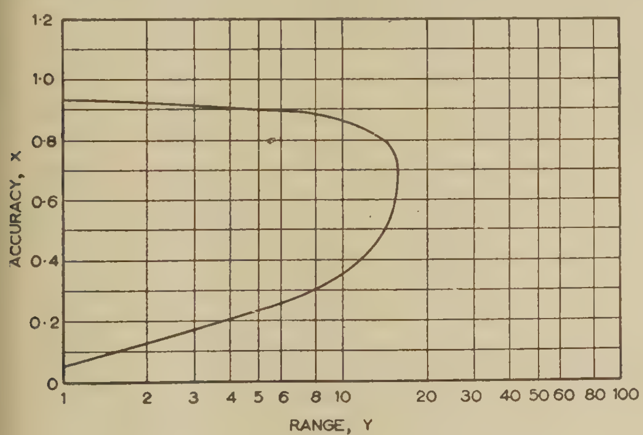


Fig. 11.—Accuracy/range curve of pulse-type relay.

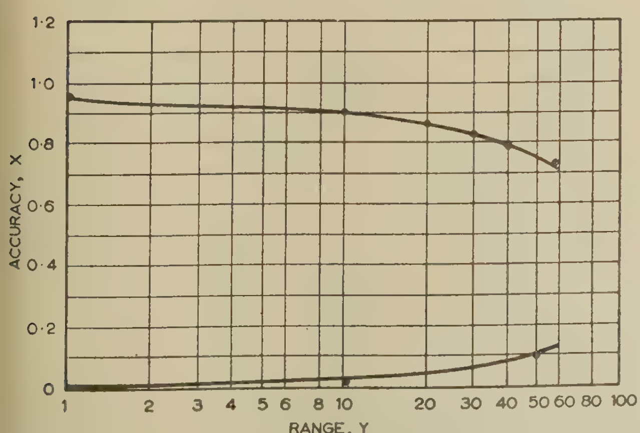


Fig. 12.—Accuracy/range curve of direct-phase-comparison relay.

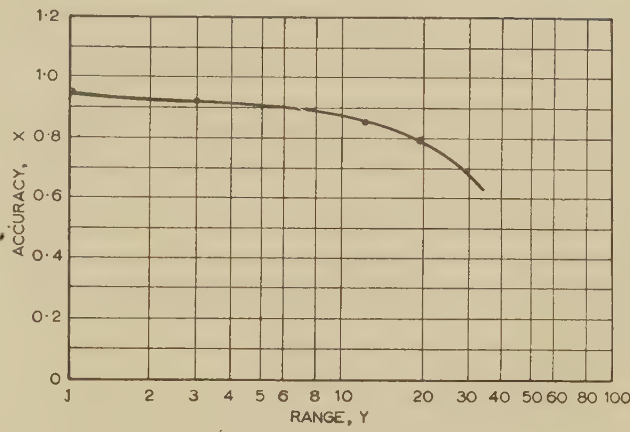


Fig. 13.—Accuracy/range curve of pulse-type relay with external polarization.

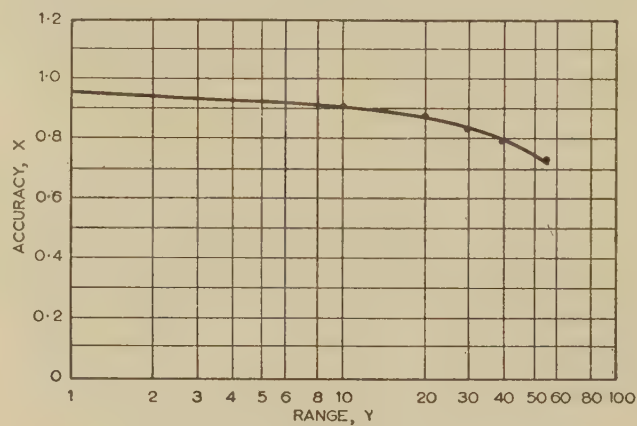


Fig. 14.—Accuracy/range curve of direct-phase-comparison relay with external polarization.

(7.3.1) Pulse-type Relay.

Reference to Fig. 11 shows the fall of accuracy with range for this type of relay. Referring to the equivalent circuit of Fig. 8(*a*), this is due to the small negative bias on the transistor T_2. At balance $I_L Z_{R2}$ is equal to $k_2 V_L$, and in an ideal relay would cause the transistor T_2 to switch off. In practice, this is not permissible since the relay would then operate for the condition $V_L = V_2 = 0$; the negative bias ensures that this situation does not occur. At balance $(I_L Z_{R2} - V_{bias})$ is equal to $k_2 V_L$. The impedance presented to the relay is

$$Z_L = \frac{Z_{R2} - (V_{bias}/I_L)}{k_2}$$

Thus, since I_L decreases with increasing range, the value of Z_L at balance falls as shown in the accuracy curves.

The curves also show that over the entire range, below certain accuracies, the relay fails to operate. V_L falls in magnitude for a feeder fault close to the relay terminals. A point is reached at which V_L is insufficient to produce the bias and T_3 [Fig. 8(*a*)] can no longer switch off. The accuracy at which this effect first becomes apparent increases with the range. Eventually this curve intersects with the boundary accuracy/range curve giving

the overall curve of Fig. 11. Thus the shaded area of Fig. 11 represents the operating zone of the relay. It may be observed that the biases on the transistors T_2 and T_3 are analagous to the torque required to overcome static friction in an electromagnetic relay.

Fig. 13 shows the accuracy/range curve for the same relay when it is receiving polarizing voltage from an unfaulted phase. Again the accuracy at the balance point falls with increasing range for the reasons given above, but the second effect is absent, since the pulse amplitude is always sufficient to overcome the bias on T_3 at the appropriate instant. The implication of polarizing from an unfaulted phase is therefore that the relay will preserve its characteristics down to the origin, i.e. for a fault actually on the relay terminals.

(7.3.2) **Direct-phase-comparison Relay.**

Reference to Figs. 12 and 14 shows the performance of the direct phase comparison relay to be comparable to Figs. 11 and 13 of the pulse relay. Inspection shows that the performance is considerably improved. This is achieved by a considerable reduction in the bias of the transistors T_1 and T_2 in Fig. 9(*a*); the argument relating to the effect of bias on performance of T_1 and T_2 in this case is essentially the same as for the pulse-type relay.

(7.3.3) **Transient Overreach.**

The phenomenon of a relay operating, under transient conditions, for impedances greater than its setting is known as 'transient overreach'. The transient-overreach factor is the impedance at which the relay just operates, expressed as a fraction, or a percentage, of the relay setting. Transient overreach is a fundamental limitation of fast-operating relays of this type; a figure greater than 1·05 is undesirable, and a figure of 1·10 is usually unacceptable.

Fig. 15 shows the transient-overreach factor, for both relays,

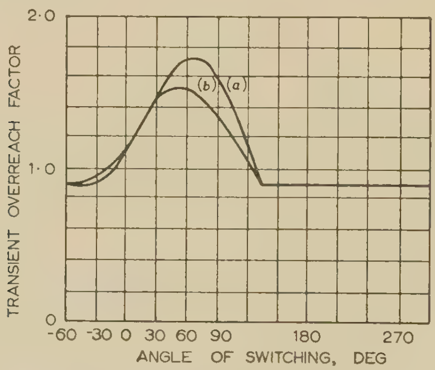


Fig. 15.—Transient overreach.
(*a*) Pulse-type relay.
(*b*) Direct phase comparison relay.

plotted against the angle on the voltage wave at which the fault occurs; the results were taken for a range of 8 : 1. It will be observed that the transient-overreach factor is constant over a total angle of 180°; during the remaining 180°, the overreach increases and has peaks of 1·7 and 1·5 for the pulse and direct-phase-comparison relays, respectively.

The mechanism of transient overreach may be explained by the presence of d.c. transient components appearing in the voltage $(I_L Z_{R2} - k_2 V_L)$, which, in the previous analysis, has been assumed to be sinusoidal. Thus in Figs. 8(*a*) and 9(*a*) a positive transient component will offset the negative bias appearing on the bases of T_2 and T_1, respectively. In consequence, at balance, these transistors are switched off and allow measurement to proceed; it is necessary for $k_2 V_L$ to be greater than $I_L Z_{R2}$ for this transient component to be overcome. For the case of negative transient components appearing at T_2 and T_1 in Figs. 8(*a*) and 9(*a*), respectively, the negative bias is assisted; thus measurement is delayed until the transient decays, but no overreach will take place.

It may be shown (see Appendix 11.2) that the voltage V_S (Fig. 6) appearing at the secondary terminals of the transformer reactor is substantially free from any d.c. transient component which may be present in its exciting-current wave. Under the worst conditions in these tests, corresponding to 100% current transient, this d.c. component is never greater than 0·12. It is therefore necessary to seek elsewhere for the very severe transient overreach recorded in Fig. 15. Appendix 11.3 shows how a transient component in the wave of fault current is indirectly responsible for a transient appearing across the voltage-transformer line terminals. This component receives negligible attenuation and, in consequence, appears at the relay input terminals. Since this component is a function of the

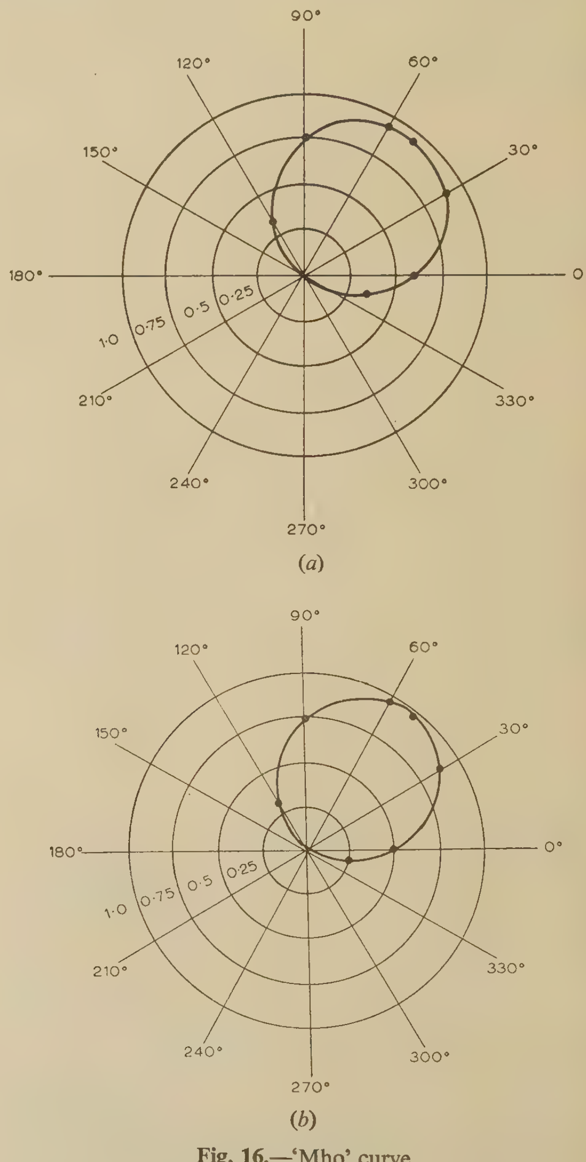


Fig. 16.—'Mho' curve.
(*a*) Pulse-type relay.
(*b*) Direct-phase-comparison relay.

difference between the source and line reactance/resistance ratios, this transient overreach will not manifest itself on a bench which does not completely simulate the power system. Frequently a tapped line is used in distance-relay tests, and since this arrangement is homogeneous, line and source reactance/resistance ratios are equal and no transient component will appear across the line voltage-transformer terminals. Hence virtually no transient will appear across the input to the relay because of the attenuating effect of the transformer reactor to d.c. transients, and the relay performance characteristics so determined would be optimistic.

(7.4) Static 'Mho' Characteristics

The 'mho' curves for the two relays are shown in Figs. 16(*a*) and 16(*b*); these curves show close agreement with theory.

(7.5) Timing

The operating time of the relays was short. This feature was not, however, investigated fully, since the difficulties experienced with transient overreach (Section 7.3.3) were so severe that the phenomenon merited prior consideration.

(8) CONCLUSIONS

Junction transistors may be used as functional switching circuits in protective-gear relays; as other transistors of higher ratings become available the range of usefulness in this application will widen.

There are a number of advantages and disadvantages associated with the use of junction transistors, and these fall into two main categories, namely those which are common to all transistor circuits and those which apply only to the relays described in this paper. Transistors suffer from the general disadvantage that they require external power supplies varying from 2 to 10 volts d.c. The power drain from the batteries is very small (of the order of 5–10 mA for the relays described), and it may be concluded that limitation (*f*) of Section 2.2 has been partially removed.

Transistor relays have the advantage over electromagnetic relays in that the sensitivity is very high, owing to the large current gain obtainable. This results in an overall reduction in burden, particularly on voltage transformers.

The pulse-type relay suffered from the disadvantage of instability in the presence of stray disturbances. Thus, in its present form it would be completely unacceptable, and work on it has been discontinued in favour of the direct-phase-comparison type of relay; this does not suffer from such instability. The phase-comparison type of relay has the advantage of high sensitivity and has an effective range of approximately 22; with current compensation this could be extended considerably.

Both relays were susceptible to the presence of d.c. transient components in the restraint voltage. This is a fundamental limitation and could probably be overcome by following one of two lines of thought. Either the d.c. component could be reduced to an acceptable value by inserting a suitable network between the voltage transformer and the relay, or use could be made of the fact that the relay tends to underreach and overreach on alternate half-cycles. A circuit could be designed which responded to the average value over a complete cycle, in which case the transient overreach could be reduced to a very small value, even under the worst conditions.

From Section 2.1, it will thus be seen that transistors are highly competitive with conventional electronic equipment applied to power-system distance protection. So far as the limitations of Section 2.2 are concerned, (*e*) is eliminated and (*f*) is partly removed. It may thus be seen that, once the problem of transient overreach (*g*) has been solved, few technical difficulties will remain.

The life of transistors is, at present, unknown, although it is claimed that their operating life at normal rating will be many times that of conventional thermionic valves, and that their shelf life is almost indefinite. Progress and development in transistors is rapidly bringing their rating and power into a situation where they will be of real practical value in the design and development of new protective-gear systems and relays.

(9) ACKNOWLEDGMENTS

The authors wish to acknowledge the advice and assistance of their colleagues in the Department of Electrical Engineering, College of Technology, Manchester, particularly that of Mr. B. D. Nellist, M.Sc.Tech., and the co-operation and advice received from the Research and Certification Department of A. Reyrolle and Co., Ltd.

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(11) APPENDIX

(11.1) Criterion for Relay Operation

From Figs. 2(*a*) and 2(*b*), let

$$V_1 = a + jb = V_1\angle\alpha_1 (= k_1 V_L + Z_{R1} I_L)$$

$$V_2 = c + jd = V_2\angle\alpha_2 (= k_2 V_L + Z_{R2} I_L)$$

Then $$\frac{V_1}{V_2} = \frac{ac + bd + j(bc - ad)}{c^2 + d^2} = \frac{V_1}{V_2}\angle\alpha_1 - \alpha_2$$

$$= \frac{V_1}{V_2}\angle\alpha$$

and $$\cos\alpha = \frac{ac + bd}{\sqrt{[(ac + bd)^2 + (bc - ad)^2]}}$$

The criterion for operation of the relay is that

$$-90^\circ < \alpha < +90^\circ, \quad \text{i.e. } \cos\alpha > 0$$

Therefore $$ac + bd > 0$$

Only the case for which k_1 and k_2 are real numbers will be considered, and V_L will be taken as the reference vector, i.e.

$$V_L = V_L\angle 0^\circ$$

Writing
$$I_L = I_L\angle -\phi_L$$
$$Z_{R1} = Z_{R1}\angle\theta_1$$
$$Z_{R2} = Z_{R2}\angle\theta_2$$

$$V_1 = k_1 V_L + Z_{R1} I_L\angle\theta_1 - \phi_L$$
$$= k_1 V_L + Z_{R1} I_L \cos(\theta_1 - \phi_L) + jZ_{R1} I_L \sin(\theta_1 - \phi_L)$$
$$V_2 = k_2 V_L + Z_{R2} I_L\angle\theta_2 - \phi_L$$
$$= k_2 V_L + Z_{R2} I_L \cos(\theta_2 - \phi_L) + jZ_{R2} I_L \sin(\theta_2 - \phi_L)$$

Therefore

$$ac + bd$$
$$= [k_1 V_L + Z_{R1} I_L \cos(\theta_1 - \phi_L)][k_2 V_L + Z_{R2} I_L \cos(\theta_2 - \phi_L)] + Z_{R1} Z_{R2} I_L^2 \sin(\theta_1 - \phi_L)\sin(\theta_2 - \phi_L)$$
$$= k_1 k_2 V_L^2 + V_L I_L [k_1 Z_{R2}\cos(\theta_2 - \phi_L) + k_2 Z_{R1}\cos(\theta_1 - \phi_L)] + Z_{R1} Z_{R2} I_L^2 \cos(\theta_1 - \theta_2)$$

Thus the criterion for operation of the relay becomes

$$k_1 k_2 V_L^2 + V_L I_L [k_1 Z_{R2}\cos(\theta_2 - \phi_L) + k_2 Z_{R1}\cos(\theta_1 - \phi_L)] + Z_{R1} Z_{R2} I_L^2 \cos(\theta_1 - \theta_2) > 0$$

Let $$Z_L = \frac{V_L}{I_L} = \frac{V_L}{I_L}\angle\phi_L = Z_L\angle\phi_L$$

(the impedance presented to the relay terminals). Then

$$k_1 k_2 Z_L^2 + Z_L[k_1 Z_{R2}\cos(\theta_2 - \phi_L) + k_2 Z_{R1}\cos(\theta_1 - \phi_L)] + Z_{R1} Z_{R2}\cos(\theta_1 - \theta_2) > 0$$

(11.2) Transient Response of Transformer Reactor

Fig. 17 is a schematic of the test line and the transforme reactor Q, all referred to the relay input terminals. All relevan quantities are shown in the Figure, and only the case of 100% transient in the fault current will be considered, i.e.

$$i_L = I_{Lmax}(\cos\omega t - \varepsilon^{-\omega t/\tan\phi})$$

It may be shown that the secondary voltage is

$$v_s = \omega M I_{Lmax}\cos\phi_2\left[\cos(\omega t + \pi/2 - \phi_2) + \frac{\varepsilon^{-\omega t/\tan\phi}}{\cos\phi_2(\tan\phi - \tan\phi_2)} - \sin\phi_2\varepsilon^{-\omega t/\tan\phi_2} - \frac{\varepsilon^{-\omega t/\tan\phi_2}}{\cos\phi_2(\tan\phi - \tan\phi_2)}\right]$$

The last two terms in this expression may be disregarded fo the case under consideration. The transformer reactor wa matched to the line impedance, i.e. $\pi/2 - \phi_2 = \phi_L$ and thu $\tan\phi_2 = 1/\tan\phi_L = 0{\cdot}5$. Therefore the time-constant

$$\frac{\tan\phi_2}{\omega} = \frac{0{\cdot}5}{314}\times 10^3 = 1{\cdot}6\,\text{millisec}$$

is sufficiently small to be neglected, its main effect being to redu the rise time of the primary transient,

$$\frac{\varepsilon^{-\omega t/\tan\phi}}{\cos\phi_2(\tan\phi - \tan\phi_2)} = K_A\,\varepsilon^{-\omega t/\tan\phi}$$

K_A is a measure of the per-unit transient appearing in th voltage v_s $\tan\phi$ varied between the limits 50 and 10 in the test giving limits for K_A of $0{\cdot}022$ and $0{\cdot}12$ respectively.

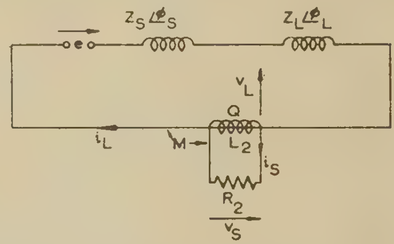

Fig. 17.—Equivalent circuit of line and transformer reactor referred relay input terminals.

$$Z\angle\phi = R + jX$$
$$= Z_S\angle\phi_S + Z_L\angle\phi_L$$
$$\phi_2 = \arctan\frac{\omega L_2}{R_2}$$

(11.3) D.C. Component in Fault Voltage

From Fig. 17, it may be shown, by solution of the equation fo the circuit, that the relay voltage v_L may be expressed as

$$v_L = V_{Lmax}[\cos(\omega t + \phi_L) + K_B\varepsilon^{-\omega t/\tan\phi}]$$

where $$K_B = \cos\phi_L\left(\frac{\tan\phi_L}{\tan\phi} - 1\right)$$

Using the values for ϕ_L and ϕ as in Appendix 11.2, the limitir values for K_B are $0{\cdot}43$ and $0{\cdot}36$, respectively; this transie component thus accounts predominantly for the transie overreach.

Paper No. 2132
Aug. 1956

LIGHTING

A Review of Progress

By J. W. T. WALSH, O.B.E., M.A., D.Sc., Member.

(1) GENERAL PRINCIPLES AND MEASUREMENTS

The most important development in light measurement has been the adoption of a primary standard, as foreshadowed in the last Review.* The old flame standards (Vernon Harcourt pentane, Hefner, etc.) had long been abandoned as unsatisfactory, and all photometric measurements were referred to a unit of luminous intensity preserved by means of a number of filament lamps held at the various national standardizing laboratories. Secondary standards, measured by comparison with these lamps, were exchanged between the national laboratories from time to time, to secure consistency, but there was no absolute standard, i.e. one which could be reproduced from specification.

As the result of research carried out at the National Bureau of Standards, Washington, it was suggested that a small cavity radiator (black body) at the temperature of solidification of platinum should be used, and experiments at the various national laboratories showed that this form of standard could be reproduced to an accuracy within about ½%.

Further work was done and inter-comparisons were made between the national laboratories, the results being reported to the Comité International des Poids et Mesures.[1] The adoption of the new standard was delayed by the outbreak of war, but the work was resumed later and the new standard was adopted by all countries, signatories to the Metre Convention, on the 1st January, 1948.[2] The new unit was defined as one-sixtieth of the luminous intensity per square centimetre of a full radiator (black body) at the temperature of solidification of platinum. This unit was very close to the accepted value of the international candle, the difference being less than 1% for the commonly used light sources.[3] On the same date Germany abandoned the Hefner unit, which was approximately nine-tenths of the international candle, and adopted the new unit. This was at first called the 'new candle', but as the result of a proposal by the Commission Internationale de l'Éclairage in 1948,[4] the name was changed to 'candela'.

During the last 15 years visual photometry has been largely replaced by photo-electric methods of measurement. In the laboratory, both for precise measurement and for routine work of less precision, photo-emissive cells are most frequently employed, especially where high sensitivity is required, but photo-voltaic cells are also used. A number of papers describing the various methods of use have been published.[5] In most cases the light from the sources to be measured differs in colour to a greater or less extent from that of the secondary standards used, and it is therefore necessary to correct for the difference between the sensitivity curve of the cell and that of the conventional 'average eye' adopted by international agreement. This correction may be made by means of colour filters, either glass or stable chemical solutions.[6] Alternatively, the so-called 'dispersion and mask' method may be used; in this, the light, before it reaches the photocell, is dispersed by means of a prism or otherwise, and a template of suitable shape is placed in the plane of the resulting spectrum. The light which passes through the template is then recombined and falls on the photocell, the shape of the template being such that light of any given wavelength is weighted by a factor proportional to the ratio of the sensitivity of the average eye to that of the cell at that wavelength.[7]

In general, the photo-emissive cells used are of the vacuum type, because of their greater stability. For measuring light of very low intensity a multiplier photocell is sometimes used.

For the measurement of illumination outside the laboratory, a number of types of photometer incorporating a photo-voltaic cell and a milliammeter are available. There are two chief sources of error: one is the spectral sensitivity of the cell, which is relatively greater than that of the eye at the blue end of the spectrum; the other is the so-called 'cosine error'—the progressive loss of sensitivity as the angle of incidence of the light on the surface of the cell is increased. At angles exceeding 60° this may give rise to serious errors. The spectral sensitivity may be corrected by the use of a colour filter, but this both reduces the overall sensitivity of the instrument and increases the cosine error, owing to reflection from the surface of the filter. For work to the accuracy generally required in engineering practice, it is sufficient to apply a correction factor according to the particular source of light furnishing the illumination measured. A series of such factors for commonly used light sources, determined for the particular type of cell used, is given in a Table attached to the instrument; alternatively, a series of shunts to the milliammeter are provided. Numerous devices have been proposed to overcome the cosine error, but none has been generally adopted. The error is not usually important in interior lighting, but precautions have to be taken to avoid it in certain types of measurement, particularly in street lighting.

Certain changes of nomenclature have been made, either by national or by international agreement. The candela (cd) has already been mentioned. Brightness, in its physical aspect as the property of a body emitting or reflecting light, is now called 'luminance' in precise phraseology.[8] It is measured in candelas per unit area or in terms of the luminance of a perfectly diffusing surface emitting or reflecting one lumen per unit area. If that area is one square foot the unit is the foot-lambert (ft-L), the corresponding metric unit being the apostilb (asb). The foot-lambert is similar in magnitude to the millilambert, now falling into disuse:

$$1\,\text{ft-L} = 1{\cdot}076\,\text{mL} \doteq 1/\pi\ \text{cd/ft}^2$$

The unit of illumination used in this country and in America was formerly called the foot-candle. This name has now been dropped in this country (but not in the U.S.A.) in favour of the more self-explanatory lumen per square foot (lm/ft^2).

A revised and extended 'Glossary of Terms used in Illumination and Photometry' (B.S. 233) was published in 1953 by the B.S.I. A similar 'Glossary of Colour Terms used in Science and Industry' (B.S. 1611) was published in the same year. An extensive international lighting vocabulary, giving definitions in English, French and German, of hundreds of terms used in lighting is to be published shortly by the Commission Internationale de l'Éclairage.

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Dr. Walsh is a lighting consultant.

(2) LAMPS

(2.1) Tungsten-Filament Lamps

In lamps of the general-lighting-service (g.l.s.) type there have been no very notable advances since the last Review. Efficiencies have been generally increased by a few per cent, and in some ratings the bulb size has been reduced. A new diffusing bulb has been introduced, the inside surface of the glass being coated with a thin layer of silica.[9] The bulb appears to have a very uniform brightness which is much lower than that of the bright patch in a pearl lamp; the loss of light is about 5%. A completely revised British Standard has just been issued to replace the 1940 edition with its 13 amendment slips.[10]

The number of types of special lamp has been considerably increased. Projector lamps are now available in a wide range of ratings and filament shapes.[11] For cinema and television studio work higher ratings have been made, the latest being a 20 kW lamp with a light output of over half a million lumens.[12] A combination of lamp and reflector is the 'reflector spotlight' introduced some years ago particularly for shop lighting and similar work; one half of the bulb is paraboloidal in shape and internally silvered so as to concentrate much of the light in the forward direction.[13] Specially designed lamps are now used extensively for heating and drying by infra-red radiation, while others which give a certain amount of ultra-violet radiation are used for germicidal purposes. These applications, however, lie outside the scope of this Review.

(2.2) Discharge Lamps[14]

The mercury-vapour and sodium-vapour discharge lamps have undergone no major developments since the last Review, but efficiencies and life have been increased.[15] For sodium-vapour lamps the average efficiency throughout the life of 4000 hours is now 50 lm/watt for the smallest rating (45 watts) and 65 lm/watt for the largest (140 watts). The corresponding figures for mercury-vapour lamps are 29 lm/watt for the smallest (80 watt) lamp and 34 lm/watt for the largest (400 watts);[16] the 250 and 400-watt lamps are normally constructed for vertical burning, but lamps which can be used in the horizontal position are now available, although the efficiency is some 8–10% lower.

The mercury–tungsten lamp, in which a tungsten filament and a mercury-vapour discharge lamp connected in series are mounted in a single bulb, has the convenience of requiring no ballast or capacitor for power-factor correction; the colour of the blended light, too, may be preferred to that of the mercury-vapour lamp alone. The efficiency is naturally less, namely 13–21 lm/watt (average throughout life) according to the rating. The filament is under-run to give a life of about 3000 hours.[16]

The most spectacular development is the introduction of the electronic flash-lamp, in which a high-current-density discharge takes place in a straight or spiral tube filled with xenon at low pressure.[17] The lamp is connected across a bank of capacitors, which are trickle-charged by means of a rectifier and transformer operating on an a.c. or interrupted d.c. supply. The voltage builds up to a value which is not quite sufficient to cause the discharge to take place. The flash is then produced by means of a trigger circuit which is operated either manually, or automatically by some very transient phenomenon which is to be studied. The flash speed, generally measured in microseconds, is a function of the capacitance employed; the light output is a function of the voltage, usually several kilovolts; the output is often measured in joules. The spectrum of the light emitted consists of many lines well distributed over the visible spectrum and the colour of the light is similar to that of daylight. The lumen-seconds may be taken as about 40 per joule.

A continuous discharge through xenon at a pressure of about 2 atm provides a light source which has been found suitable f[or] colour matching and other purposes. The efficiency is fro[m] 22 to 30 lm/watt according to size. This type of lamp is still [in] course of development.[18]

Both the mercury- and the sodium-vapour lamps suffer fro[m] the disadvantage that the colours of objects seen by their lig[ht] are badly distorted. With the mercury lamp a partial correcti[on] may be obtained by causing the discharge to take place in [an] inner tube of quartz, which transmits the ultra-violet radiati[on] produced. This inner tube is mounted inside a larger glass bu[lb] with an internal coating of some phosphor, which both fluoresc[es] under the action of the ultra-violet radiation and transm[its] much of the visible light produced by the discharge.

The first lamps of this kind were bulky, because the phospho[rs] used deteriorated rapidly if they were heated above abo[ut] 150° C, as mentioned in the previous Review. During the pa[st] few years, however, developments in the manufacture of pho[s]phors have made it possible to produce lamps of this type [in] much smaller bulbs and with better colour correction.[19] The[se] lamps, generally known as colour-corrected mercury-vapo[ur] lamps, are now made in a number of ratings from 80 to 400 wat[ts]. The efficiency is rather better than that of the normal uncorrect[ed] mercury-vapour lamp, namely 32–37 lm/watt (average througho[ut] life). These lamps are very widely used for street lighting on t[he] Continent, and their use similarly in this country may w[ell] increase in the near future.

(2.3) Fluorescent Lamps

Undoubtedly the most important development in light sour[ces] to be noticed in this Review is the widespread introduction of [the] fluorescent lamp. This made its first appearance in 1938—[–] just in time to be mentioned in the last Review, but the on[ly] kind then available in this country was the 5 ft tubular la[mp] rated at 80 watts. The outbreak of war created a huge dema[nd] for these lamps, because in many of the factories which w[ere] suddenly called upon to work night and day the lighting instal[lation] was antiquated and totally inadequate for continuous work [at] night or under conditions of black-out. To increase the light [to] to a satisfactory level by the use of more or larger tungst[en-] filament lamps would have meant complete rewiring in ma[ny] instances, and the availability of the fluorescent lamp, giv[ing] approximately four times as much light for the same pow[er] consumption, saved the situation. At the same time, the sudd[en] demand made it necessary to concentrate attention on the o[ne] size of lamp required for immediate use and this held up devel[op]ment, so that it was not until some years after the end of [the] war that the range of sizes available was increased and ot[her] improvements could be made.

Since then there has been steady progress.[20] Efficiencies a[nd] life performance have been improved, but more important [has] been the development of new phosphors giving a range of to[nes] of so-called 'white' light. The introduction, about 1948, of [the] calcium halophosphate phosphors [$3Ca_3(PO_4)_2 . CaX_2$, wh[ere] X may be Cl or F] made possible the production of lamps giv[ing] an almost infinite variety of colours over a fairly wide ra[nge] without sacrifice of efficiency.[21]

If the light emitted by the lamp were only that given by [the] phosphor, it would be a comparatively simple matter to des[ign] a lamp under which the colours of objects would appear [as] 'natural' as they do under a tungsten-filament lamp or un[der] daylight. Unfortunately, there is a strong emission from [the] low-pressure mercury discharge at a wavelength in the blue-vio[let] and this is only partially absorbed in the phosphor. The res[ult] is that the spectral distribution of the light from a fluoresc[ent] lamp has a marked peak at this wavelength, and there is con-

quently some degree of colour distortion when objects of certain colours are illuminated by this light. Much work has been done, and is still continuing, to reduce this colour distortion without too great a loss of efficiency, and progress is being made, although it is necessarily slow.

Work is also needed to produce a specification for light with satisfactory colour-rendering properties. The ordinary spectral-distribution curve cannot be used for the purpose, because of the strong emission at certain wavelengths which is superimposed on the continuous spectrum. There is a noticeable tendency at present to describe the spectral composition of the light from a fluorescent lamp by the relative emission within eight bands of wavelengths which together cover the whole of the visible spectrum.[22] These spectral bands have not all the same width, expressed in terms of wavelength, but they have been chosen so that, on the average, they have equal weight as far as the colour-rendering properties of the light are concerned. A further complication is introduced by the behaviour of the eye, which partially adapts itself to the colour of the light under which it works, so that the colour distortion experienced is less than that which would be predicted by physical measurement.[23]

It is perhaps appropriate at this point to mention that, contrary to statements made from time to time, the amount of ultra-violet radiation from the ordinary fluorescent lamp is exceedingly small: for equal values of illumination it is considerably more intense in sunlight.[24]

The alleged danger from ultra-violet radiation is only one of the criticisms which have been levelled at the fluorescent lamp. The fact that on the normal mains supply the light is periodic, with a frequency of 100 c/s, has been put forward as a cause of the discomfort which is occasionally experienced with fluorescent lighting when first installed. In general, investigation has revealed that the discomfort is due to bad design of the installation; in particular, neglect to take suitable precautions against glare. Because the brightness of the lamp is much lower than that of, say, a tungsten filament lamp, it has not infrequently been assumed that there is no need to shield it from view. This mistake is becoming less prevalent and complaints of discomfort are correspondingly rarer. It is noticeable that, whenever a new source of light has been introduced, vague complaints and criticisms have invariably been made, only to die out as time removes the novelty, which, consciously or not, is the chief cause of the disquiet. Trouble from stroboscopic effects has been found in practice to be much more infrequent than was at first expected; where it is present it can be overcome by mixing the light from two or more lamps with their light cycles out of phase.

A real disadvantage of the fluorescent lamp is that the circuit is much less simple than that of the filament lamp. Some kind of stabilizer has to be introduced, and this generally takes the form of a choke or a leakage transformer; on direct current an ordinary resistor (or a filament lamp) can be used, but the efficiency is much lower and special means have to be taken to change the polarity frequently. The use of a choke or transformer reduces the power factor, so that a capacitor has to be inserted across the mains; correction to a power factor of about 0·85 is general. Until comparatively recently a special device had to be included in the circuit to act as a starter for the lamp, but it is now becoming common to use a different form of circuit which, with a slight modification to the lamp, enables the starter to be dispensed with, although the life is somewhat reduced. It may be mentioned here that the life of a fluorescent lamp, unlike that of a tungsten-filament lamp, is affected by the frequency of switching; the figures given for life are based on an average of three hours' operation at a time.

It is impossible here to deal with the various forms of circuit which are used with fluorescent lamps, but they have been described in detail in a number of publications.[25]

An important modification of the ordinary fluorescent lamp which is increasing in popularity, especially for large installations, is the cold-cathode lamp which operates without a starter on a high-voltage circuit.[26] The lamp may be of any length, but below the standard length of 9 ft 6 in it becomes increasingly inefficient. The voltage required depends on the length; for the standard length it is 3·6 kV for starting and 1·9 kV under running conditions, the current being 120 mA. One great advantage is the long life, which is of the order of 15 000 hours and is not greatly affected by the frequency of switching. The efficiency is approximately the same as that of an 80-watt fluorescent lamp of the normal (hot-cathode) type giving light of the same colour.

To conclude this brief review of developments in electric lamps, reference must be made to a form of light source which is at present in a very early stage of development. This is, in essence, a large condenser, one plate of which is transparent, while the dielectric consists of a thin layer of a suitable phosphor. When an alternating voltage is applied across the plates of the condenser the phosphor glows with a low brightness. The transparent plate is a sheet of glass with a conducting layer on one surface. The efficiency is low but rises with the frequency of the applied voltage.[27]

(3) FITTINGS

There have been several attempts to popularize in this country the use of the term 'luminaire', which is almost universally employed in the United States to denote what is generally known here as a 'lighting fitting'. Success has been only partial.

The chief developments to record are those brought about by the introduction of new materials, notably light alloys for the metal components and plastics for the parts previously made of glass. Plastics are also used sometimes to replace metal, so that there are now street-lighting fittings, for example, which are made almost entirely of moulded plastics.[28] Aluminium alloys are especially suitable for die-casting, and the importance of accuracy in many modern fittings with optical elements has greatly increased the use of this material.[29] In certain circumstances, particularly when a fitting is used out of doors at the seaside, or in an industrial area where it is subject to chemical fumes, corrosion may be troublesome and special precautions have to be taken when aluminium alloys are used under such conditions. Anodized aluminium is now extensively used for reflector elements in place of back-silvered glass.[30]

The availability of plastics has fortunately coincided with the widespread introduction of the tubular fluorescent lamp, for the fittings needed to accommodate these lamps are necessarily bulky and, if made in metal and glass, of considerable weight. Thermoplastics such as the polymerized methyl methacrylate (known in this country as Perspex) are used extensively, either in the clear form or as diffusers.[31] An important limitation of certain of these materials is that they tend to soften at temperatures above about 80° C, so that unless the design of the fitting is such that this temperature is nowhere exceeded in operation, the fitting may become distorted. Fortunately the fluorescent lamp is a 'cool' source of light, so that it is not difficult to avoid the trouble in most cases.

Interior lighting fittings for use with fluorescent lamps may be divided broadly into two classes. There are first the inverted trough fittings of simple design housing one or more lamps. The trough may be opaque, or translucent with a comparatively low transmission and a high reflection factor. The mouth of the trough may be open or covered with a so-called louver or mesh of thin vertical strips, so designed as to prevent direct view of the lamp except by looking upwards at an angle of 45° or more

These fittings are of the direct or semi-direct types, i.e. the greater part of the light is emitted downwards. Then there is a class of fittings of which a shallow open dish with diffusing sides and a louver bottom is typical. The upward light from the lamps is not obstructed in any way, and the overall light distribution is of the 'general diffusing' type, i.e. there is no marked preponderance of either upward or downward light. There are many variants of both types, and the construction may be of metal or plastic or both.

It is appropriate to mention here a development in lighting which, while not strictly a fitting, is somewhat akin to the first class of fittings described in the previous paragraph. This is the louver ceiling, in which an extensive grid or mesh, constructed of thin vertical strips of metal or translucent plastic, forms a false ceiling below the fluorescent lamps.[32] These are mounted fairly close to the true ceiling of the room, which must be kept white if the system is to be reasonably efficient. Maintenance is a serious problem, and the louver ceiling is usually sectionalized, the sections being light and easily removable for cleaning. The system was introduced to enable high values of illumination on the working plane to be obtained without glare, and with proper precautions the results are excellent. It is, for instance, possible to enjoy an illumination of 100 lm/ft^2 or more with complete comfort and freedom from glare. Great care, however, must be taken to avoid shiny surfaces, which can, and frequently do, cause very objectionable glare by reflection.

An increasing number of industrial processes result in the production of inflammable vapours or of very fine dusts, with a resultant explosion risk unless suitable precautions are taken, and statutory requirements are laid down with regard to the construction of lighting fittings used in such locations.[33] In the first place it must be impossible for any explosion which may occur inside the fitting to ignite the external atmosphere, and the mechanical strength of the fitting, including the glass, is tested to ensure that this requirement is fulfilled. A further requirement is that propagation of flame through a joint must be prevented, and to ensure this any joint must have metal flanges of a specified width, generally about 1 in. The metal surfaces must be machined so that the gap nowhere exceeds a specified value ranging from 8 to 20 mils according to the nature of the inflammable vapour. Finally, the surface temperature of the fitting when in operation must nowhere exceed 50° C for an ambient of 15°–35° C. There are a number of fittings made to satisfy these requirements, and these are certified and given the F.L.P. mark after tests made by the Ministry of Fuel and Power.

When certain gases such as hydrogen or acetylene may be present in the atmosphere, even flameproof fittings may not be used. Such premises must be lit entirely from outside or a pressurized system must be used in which fittings, conduit and all accessories form a single hermetically sealed unit charged with air or carbon dioxide to a pressure of about 5 lb/in^2. A series of switches are incorporated at various points to cut off the supply if this internal pressure falls.[34]

In street lighting the advent of the discharge lamp resulted in the production of a number of new types of fitting.[35] The vertical-burning mercury-vapour lamp presented a difficult problem as regards concentration of the light in directions between 70° and 80° from the downward vertical. The sodium-vapour lamp, since it normally operated horizontally, was much easier to deal with, and magnetic devices to enable a mercury-vapour lamp to be used horizontally were produced. Probably even more productive of new types of street-lighting equipment was the rapid spread of fluorescent street lighting in this country, which undoubtedly led the world in this development. The extensive use of plastics for the rather bulky fittings needed has already been mentioned. Not only are plastics used for the case of the lantern, but moulded prismatic refractor plates are use for redirecting the light from the lamps. A single lantern ma house up to seven lamps, but two, three or four are mo commonly employed.

In conclusion, it may be mentioned that a number of Britis Standards relating to lighting fittings have been issued sinc the war. Some of these deal only with constructional matters, but others lay down limits of lighting performance as well.[37]

(4) INTERIOR LIGHTING

There are two major developments to record in lighting desig one relating to the way in which the illumination required for particular purpose is assessed quantitatively, the other to th purely qualitative aspect of a lighting system.

As the result of a series of elaborate and painstaking researche it has been established that the standard of performance of given task is related in a measurable way with the size of th smallest detail which has to be perceived, the contrast presente by details which have to be distinguished and the brightness the object of regard—a function of its reflection factor and th illumination.[38] It is found that increasing the illuminatio within reasonable limits will not make performance, when th size is very small, equal to that when it is large, but, on the oth hand, for any given size there is a certain illumination at whic the performance (embracing both speed and accuracy) is a certa high percentage of the maximum possible performance attainab with that size. The same holds good for the other facto involved, and as a result is it now possible to prescribe, for task in which size, contrast, etc., are known, the value of illumin tion at which performance falls below the best possible only b a certain definite percentage.[39] This method has been followe in arriving at the recommendations of the I.E.S. Code fo Lighting in Buildings.[40]

It will be clear that the values arrived at by the method ju described may well vary from time to time and from one count to another, because the basic percentage of best performanc if selected on economic considerations, must be affected by th relation between the cost of labour and the cost of providing given value of illumination. Since in this country the form shows an almost continuous rise, while the latter has fall considerably during the last two or three decades, it is logic to increase the percentage performance and therefore the val of illumination recommended for a particular task.

When the illumination appropriate for the work is on moderate, i.e. not much over 10 lm/ft^2, it is usual to provide th by means of a general lighting system; but an illumination mu in excess of this is usually obtained by installing a gener illumination of 6–10 lm/ft^2 and supplementing this with addition so-called 'localized', lighting designed to illuminate only t area of work.[40] This should not be confused with the loc lighting frequently used in the past to increase the illuminati over a very small area.

The assessment of the quality of lighting, as distinct from t value of illumination provided, is an exceedingly difficult matt The degree of diffusion and the colour of the light are importa factors, but probably the most noticeable is the degree of gla experienced, and the related subjects of glare and comfort lighting have received increasing attention, both from t research worker and from the practising lighting enginee during the last ten years or so. Attempts have been made arrive at a formula which will give a 'glare index' for a particul condition, taking into account the luminance of the glari source and its angular size, measured at the observer's eye, relation to the luminance of the background against which it seen.[41] A good deal of work has been done in this country the subject by asking observers to judge when, in a situati

which can be continuously varied, the glare becomes (*a*) just imperceptible, (*b*) just acceptable, (*c*) just uncomfortable and (*d*) just intolerable.[42] The importance of the word 'just' is to be noted. By this method it has been possible to establish that, for example, in order to nullify the effect of increasing tenfold the luminance of a source of a certain size, the luminance of the background must be increased by a factor of twenty or more.

As a result of work of this kind, recommendations intended to limit glare as far as practicable have been included in the I.E.S. Code to which reference was made above, but these recommendations can be regarded only as representing the best that can be done in the present state of knowledge of this very complicated subjective phenomenon.

Apart from the glare produced by a source of light, there may be interference with vision if the visual field includes large areas having very different values of brightness. This has given rise to studies of the differences of luminance which can be tolerated in a well-lighted interior; the design of a lighting system to take account of this quality factor has been termed 'brightness engineering'.[43]

A still more recent development is a study of the conditions which create a sense of comfort, using the word to denote more than just the absence of discomfort, but there is nothing to report on this at present.

In home lighting the fluorescent lamp has not found much favour.[44] There has been a general tendency towards the use of larger ratings of g.l.s. lamps, the 60- and 100-watt lamps being now the most popular sizes. An official report,[45] concerned mainly with the lighting of dwellings and schools, was published in 1944, and included a very informative survey of the existing state of lighting in dwellings. A number of recommendations were made on the standard of lighting which should be provided in the various rooms of a house; in particular, an increase in the number of socket-outlets in living rooms and bedrooms was advocated. In home lighting the appearance of the fittings by day is an important matter; there are now many fittings available which combine attractive daytime appearance with good lighting performance.[44]

The same report dealt with the lighting of schools and contained recommendations on the values of illumination to be provided in classrooms and other parts of a school. The Ministry of Education has prescribed 10 lm/ft^2 as the minimum illumination to be provided over the working area in a classroom.[46] Fluorescent lighting is used to an increasing extent in schools, especially in laboratories, workshops and assembly halls.

The lighting of offices has been the subject of another official report,[47] which also contains a very useful survey of existing conditions and a number of recommendations for a satisfactory standard of office lighting. Fluorescent lighting has become very popular in offices, and this has done much to raise the values of illumination provided.

Before the lighting of industrial premises is dealt with it may be recorded that the advent of the fluorescent lamp has greatly influenced the lighting of public buildings, an outstanding example being the lighting of the new House of Commons.[48] The fluorescent lamp has even begun to find application in stage lighting, where one of the major requirements is smooth dimming over a wide range; special circuits have been designed to provide this.[49]

A great improvement in the lighting of industrial premises took place during the war, when many factories were working night and day and a minimum illumination of 6 lm/ft^2 at any working position in such a factory was enforced. Since the war, the widespread introduction of the fluorescent lamp and the increasing use of the mercury-vapour discharge lamp, side by side with a widening appreciation of the value of good lighting, have resulted in a further general improvement; values of illumination five or even ten times as great as those provided in 1939 are now common. All types of high-efficiency source are used. In premises where the colour of the light is of secondary importance the mercury-vapour discharge lamp is popular. Sometimes the colour-corrected lamp mentioned earlier in this Review is employed, but an alternative, giving partial colour correction, is the use of an ordinary mercury-vapour lamp and a tungsten-filament lamp side by side in a combination fitting.[50]

Of all industrial locations the most difficult to light is the coal mine, especially if firedamp (methane) may be present. Until comparatively recently there was very little lighting other than that provided by the miner's portable lamp, and even now this lamp is by far the most important source of light at the coal face. The old flame lamp has now been superseded by the electric lamp, either carried in the hand or fixed to the cap, and the efficiency of these lamps has been so much improved that to-day a bulb rated at 4 volts, 0·8 amp, will give nearly 40 lumens.[51] Such a bulb, used in a cap lamp with a polished reflector, gives a narrow beam with a peak intensity which may exceed 500 candelas or, with a matt reflector, a much wider beam with a peak intensity of about 25 candelas.[52] The bulbs are krypton filled and have a rated life of 200–250 hours.

It is now common for haulage roads to have mains lighting, either with g.l.s. or fluorescent lamps, but mains lighting at the coal face presents many problems, not least the necessity for the lighting equipment to be moved forward at comparatively frequent intervals as the coal is won and the working face recedes. It must therefore be transportable, but at the same time it must be robust enough to withstand the effects of shot firing. A great deal of experimental work is being done at the present time with specially designed flameproof fittings housing either tungsten-filament or fluorescent lamps. Another development has been the design of fittings which include, besides the lamp, a generator driven by compressed air, so that no mains supply is required. Both mercury-vapour and fluorescent lamps have been used in units of this type.[53]

(5) EXTERIOR LIGHTING

The issue in 1937 of the final report of the Departmental Committee on Street Lighting was mentioned in the last Review, but before this could have much effect on the standard of street lighting in this country all exterior lighting was closed down by the outbreak of war and the consequent black-out. As soon as this was lifted, even before the end of the war, the subject was taken up again very actively and, in particular, work was resumed on the preparation of a British Standard. After some time it became apparent that a Code of Practice would be preferable, and this Code has now been published, the first part, dealing with traffic routes, in 1952 and the second, dealing with other roads, in 1956.[54]

Meanwhile local authorities, encouraged by the Ministry of Transport, continued with the installation of lighting schemes based on the Departmental Committee's report. In this the use of the illumination of the road surface as a criterion was entirely abandoned, and attention was directed to the creation of a bright road surface to act as a background against which a driver could easily distinguish objects on the roadway by silhouette vision. The important factors in an installation are the mounting height and spacing of the fittings and the way in which the light from them is distributed. In the Code of Practice three types of light distribution are distinguished: one is the cut-off type, in which no light is emitted above the horizontal and the peak of the distribution curve occurs at about 70° from the downward vertical; the other two types are non-cut-off, one with a medium-

angle beam distribution, having its maximum at about 75°, and the other a high-angle beam distribution with a maximum at 80° or more. The cut-off distribution produces very little glare, but has the disadvantage that a closer spacing (not greater than 90–100 ft) must be used. It is very suitable for central suspension over a comparatively narrow roadway, but its more general use also seems likely to extend. The other distributions can be used at spacings up to 120 ft, but they produce more glare.

Many different lanterns have been designed for use with different light sources.[55] Tungsten-filament lamps are still widely used, especially in side streets and minor through roads, although the 40-watt sodium-vapour lamp is now coming into use for housing estates because of its low running cost. For traffic routes mercury- and sodium-vapour lamps are very popular, except in shopping areas or in the central parts of towns, where the colour of these sources is considered objectionable. In these areas the use of fluorescent lighting is becoming increasingly popular.

The automatic control of street lighting is now almost universal. Time switches of various types are used most widely, being either spring or synchronous-motor driven. Setting for the variation of lighting-up and extinguishing times with season of the year may be done by hand, when a spring-driven clock is wound, or it may be fully automatic with an electric clock. Where motor drive is used, the need for resetting every clock after interruption of the supply may be avoided by using a clock with spring reserve.

There are several systems of centralized or group control: the simplest makes use of a pilot wire by means of which a relay is actuated at each lamp column, and the others depend on the injection of a signal into the network supplying the lamps. This signal may be a d.c. bias of a few volts imposed on the a.c. low-voltage mains at the substation; it is picked up at each lamp column by a polarized relay in series with a choke, which acts as a filter. In another popular system a.c. signals, either at high frequency (about 10 kc/s) or audio frequency (300–1 500 c/s), are injected into the mains from special generators. The injection may take place either on the l.v. or the h.v. side and it is picked up by a tuned-reed or other type of relay.

There are also systems of control by means of a photo-electric cell, so that the lights are switched on or off, not according to a time-table, but according to the daylight illumination so that, for example, the lamps are turned on during a period of fog or temporary darkness. Finally there is radio control, which is strongly advocated by some but for which no provision is at present made in the allocation of frequencies.[56]

Great advances have been made since the war in the design of airport lighting, and 1952 saw the issue of the British Standard Guide to Civil Aerodrome Lighting,[57] which takes into account the recommendations of the International Civil Aviation Organization. The most vital part of the navigational lighting system of an airport is the system of approach lights, threshold lights and runway lights, by means of which a pilot is enabled to make a landing at night. The principal function of the approach lights is to inform the pilot whether he is on track, or off to right or to left, to provide him with a substitute for the horizon, which may often be invisible, and to indicate whether his angle of descent is correct. An arrangement of approach lights known as the line-and-bar system, or more often the Calvert system, after its inventor, was proposed some years ago and is becoming widely adopted both in this country and abroad. The essential features are a central line of lights continuous with the centre line of the runway and a series of short transverse lines (or bars) at right angles to it and situated at intervals on the approach side and increasing in length with their distance from the threshold.[58] The apparent angle between a cross-bar and the centre line tells the pilot whether he is off track right or le[ft,] the apparent angle between a cross-bar and his frame of referen[ce] in the cockpit indicates whether he is banked, and finally t[he] lengths of the cross-bars are so graded that he can correct [his] angle of descent. Side by side with developments in the layo[ut] of the lighting system at an airport there have been great advanc[es] in the design of the fittings used.

The floodlighting of buildings has now become a recogniz[ed] feature in celebrations or rejoicings, whether local or national. There are no outstanding developments to report, but the Festi[val] of Britain and the Coronation provided occasions for displa[y] on a lavish scale.[60] Floodlighting is being increasingly used [to] enable outdoor sports to be carried on after nightfall; in pa[r]ticular, the number of football grounds with floodlighti[ng] equipment is steadily increasing, although for really impress[ive] installations of this kind it is generally necessary to go overs[eas.] An exception is the recently completed installation of floo[d]lighting at the Wembley Stadium.[61]

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The number of papers published since 1940 on different aspects [of] lighting is very large, and the list which follows is only a selecti[on] (mainly from journals published in this country) of some which d[eal] with matters specifically mentioned in this Review.

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UNDERGROUND LIGHTING IN COAL MINES

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SUMMARY

The importance of lighting below ground is emphasized and the difficulties associated therewith are outlined. Inadequate or inferior lighting produces nystagmus, and mention is made of the decline in the incidence of new cases since better lighting has been introduced.

Changes in portable lamps, with improvements in technique and to suit alterations in mining methods, are reviewed, and descriptions of typical modern equipment and methods of application are included. The importance of photometry in lamp-room practice is discussed.

Bulbs and cables for miners' lamps are considered, and improvements which have been effected in the last few years are indicated.

The desirability of extending the use of mains lighting below ground for both the roadways and the coal faces is indicated. Progress in this field is reviewed, together with descriptions of equipment and results obtained. It is pointed out that the economic aspect of the general introduction of mains lighting to coal faces will be an important factor. Developments are hindered by restrictions in the use of aluminium alloys in coal mines.

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(1) INTRODUCTION

(1.1) The Importance of Lighting in Mines

No single factor is of more importance to the mining industry than lighting. Under natural conditions it is always dark below ground, and all light must be produced artificially. Furthermore, mining is a hazardous calling requiring a continual state of awareness and an ability to recognize danger from many sources, which is impossible without adequate illumination. A man can work efficiently and give satisfactory results only if he can see what he is doing and is not hampered by inadequate illumination or annoying shadows.

Lighting has a serious effect upon morale and plays an important part in improving operating conditions below ground. In these days of shortage of man-power in the mining industry it is essential that everything should be done to encourage new entrants and to retain those workers already employed; in this respect good lighting underground can have a marked effect.

Despite the recognition of the necessity for adequate illumination in mines, particularly at working places, little attention was devoted to provision of suitable lighting for a number of years. In the past, emphasis was generally laid upon the economic factors involved, and lamps were operated as cheaply as possible. To-day, however, while the necessity for economy is still recognized, more attention is rightly devoted to the performance of lamps and to their satisfactory maintenance. This development is timely, because increased mechanization in coal mines requires greater attention to detail and demands improved lighting standards if full benefit is to be obtained from the machinery employed and the accident hazard is to be reduced to a minimum.

(1.2) The Provision of Lighting Below Ground

Special problems associated with underground lighting have prevented the adoption of orthodox systems, and have made it impossible to achieve comparable standards of illumination.

The main difficulty arises from the presence below ground o inflammable gas, which requires all the lamps and fittings use to be specially designed to eliminate the risk of ignition. Suc design features frequently affect the weight and bulk of th equipment and may prohibit the general use of mains-fed equip ment. The second important obstacle is the nature of the surfac surrounding the working places. In their natural states these ar dark in colour and are highly absorbent to the light falling upo them. Coal absorbs about 95% of the incident light, shale an carboniferous rocks, about 75%; and props, etc., about 85% compared with some 40% absorbed by whitewashed surface Much can be done by whitewashing in roadways and permanen situations, but at the coal-face, which is continually movin forward, such expedients are not practicable.

The problem is also aggravated by the restricted and con gested nature of the working places. The roadways compris comparatively narrow tunnels which are not easy to illumina without glare. Coal-faces are frequently low in height and th presence of machinery and roof supports, all of which cas shadows, make even illumination virtually impossible. The onl solution here appears to lie in the use of larger light sources, bu the avoidance of undesirable extremes of light and dark and o glare is difficult, and the best result can be obtained only b compromise.

(2) VISIBILITY IN MINES

It has become apparent in the last few years that the peculia requirements of lighting in mines demand a new approach to th problems involved. Investigators in various countries are no devoting themselves to the problems of visibility, including glar Attempts are being made to assess the illumination level require for efficient performance of the various tasks below ground an to compare these values with those reasonably obtainable i practice. Estimations of optimum fitting brightness have bee made for certain specific conditions, the object being to achiev an adequate illumination without undue discomfort glare.[37, 39,] Still further basic research on this subject is needed.

One of the principal difficulties in assessing visibility in mine is the lack of agreed standards and methods of assessing th parameters involved; attempts are to be made to achieve inte national agreement on this matter.

(3) NYSTAGMUS

One adverse effect of insufficient lighting in mines is th incidence of the eye disease of miners' nystagmus. This is usual evidenced by oscillations of the eyeballs, slow adaptation of th eyes to both light and dark and other neurotic effects. Th sufferers also have a marked dislike for bright light.

Numerous theories have been advanced to explain the cause o nystagmus, but it is generally accepted to-day that deficien illumination is the prime cause. Below a critical luminance o 0·01 ft-L the eyes cannot work normally: foveal vision an normal fixation of the eyes are in abeyance and vision is by th peripheral portion of the retina. Such conditions favour th development of eye oscillations, which in severe cases may persi even in normally satisfactory illumination. Thus, to obviate th possible development of nystagmus, the luminance of the objec

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

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normally seen must be at least 0·01 ft-L; and since the reflection factor in coal mines is so poor, a minimum illumination of 0·4 lm/ft^2 should be provided. This value was first put forward as a recommendation in the Coal Mines Report of the 'Reid Committee' in March, 1945,[3] and it is now generally accepted.

Nystagmus (except the congenital variety) is a compensatable disease and its incidence is usually measured by the number of new cases reported each year. It is extremely difficult from the figures available to assess the effects of improvements in illumination upon the disease, because other factors have a considerable influence. These include the level of employment, the effect of the call-up for the Services in war-time and general economic factors.

Nystagmus is said to have been unknown prior to the introduction of safety lamps, possibly because no compensation was payable and because the illumination with some types of naked light is reasonably good.

Little improvement in the position was noticeable when electric hand-lamps were first generally used, and it was not until the widespread introduction of cap lamps about 1938 that the figures began to improve. Cap lamps are now almost universally used in British coal mines, and the following paragraph from the report of the National Coal Board for 1954 is of particular interest, because, although no figures have been published, the statisticians must be satisfied that there has been a material reduction in the number of new nystagmus cases in recent years:

> The incidence of nystagmus among miners is falling rapidly as underground lighting improves. Work during the year (1954) was accordingly reduced and concentrated upon rehabilitation and discovering a simple diagnostic test for the disease.

(4) PORTABLE LIGHTING

In the paper the term 'portable lighting' includes those systems which involve units carried by the users, as distinct from permanent and semi-permanent fittings requiring a mains source of power.

(4.1) Naked Lights

Perhaps the earliest form of illumination used in mines was the tallow candle, which was frequently made by the user. This primitive lighting can still be seen to-day in some of the metalliferous mines of the country. Oil lamps originated with the open and the spout types of lamp, which burn fairly well in normal air velocities. The use of the small 'coffee-pot' oil lamp, worn on the miners' helmets in Scotland for many years, was probably the reason for the early universal use of the electric cap-lamp in those coalfields. Such lamps were in regular use at a Northumberland colliery until 1950. Protected oil lamps or hurricane lamps were first used below ground at pit bottoms and in haulage houses about 1880, and the acetylene lamp was first used about 1905. This latter is the most common form of naked light used in mines to-day. It is light in weight, is not easily extinguished and can be carried either in the hand or worn on the helmet. It suffers from the disadvantage of requiring the burner jet to be cleaned periodically to maintain its full light output. In general, naked lights are inferior, because they consume oxygen, produce heat and constitute a continual source of danger from fire, so that they cannot be used where there is any likelihood of inflammable gases being present. Naked lights are being replaced by electric cap-lamps in many non-fiery mines, because they do not present the disadvantages outlined above and are cheaper to operate.

In the near future the use of 'permitted lamps' will be required universally throughout those mines where they are introduced. In some mines, permitted lamps have been used only in certain dangerous parts and naked lights in other safe ones. Such a mixture of permitted lamps and open lights presents hazards and will no longer be allowed.

(4.2) Flame Safety Lamps

The dangers ensuing from the ignition of firedamp in mines led engineers to try various expedients to obtain the illumination required for working below ground without exposing the workers to risk of injury or loss of life. In shallow mines, where the workings were on a limited scale, mirrors were used to reflect the light into the working places, but this arrangement was obviously useless in the deeper workings. Attempts were also made to use the glow from partly putrescent fish and of certain fungi, but without success. The Spedding flint-and-steel mill was also used for some time, in which the light came from sparks produced by applying a flint to a rapidly rotating steel wheel.

The first successful safety lamp was invented by Sir Humphry Davy in 1815 and was in the form of an oil flame protected by a wire gauze. This type of lamp passed through many stages of development during the 19th century, and at the commencement of the present century its use was universal in 'safety-lamp mines'.

The flame safety-lamp has the advantage that, in addition to providing illumination, it can be used to indicate the presence of firedamp, by the gas cap which forms over the flame and by its final extinction in an explosive atmosphere. The flame also becomes dim or extinguishes in atmospheres deficient in oxygen or containing high concentrations of carbon dioxide. These safety features have caused the flame lamp to continue in use long after it would otherwise have been superseded by electric lamps having superior lighting characteristics. It can be safely assumed that all the oil lamps in use in British mines to-day have been retained for gas testing, and the tendency is for all such lamps to be simplified to serve this single purpose.

(4.3) Electric Safety Lamps

Although a British firm was supplying portable electric lamps as early as 1889, it was not until about 1910 that their use became at all general. In 1911 there were 4 298 such lamps in use, but by 1913 this number had risen to 37 823 and in 1922 there were 294 593.

All the early lamps were of the hand type incorporating 2-volt lead-acid batteries, and this design continued to be generally used until about 1934, when 2-cell alkaline-battery lamps with a much greater light output were introduced from Germany. New legislation was introduced in 1934 requiring higher approval standards for lamps for use at important positions below ground. Initially these standards could be met by only the 2-cell alkaline lamps, but shortly afterwards the 4-volt lead-acid hand lamp was developed very much in the form in which it is known to-day.

The earliest cap-lamp models were produced even before 1910, and the first approval was granted by the Mines Department of Great Britain about 1920; but it was not until almost 1930 that electric cap-lamps were used to any material extent. They first found popularity in Scotland, where they are now exclusively used.

Fig. 1 shows the growth of the number of cap lamps in use in British mines and the corresponding decrease in hand lamps since 1928. To-day, cap lamps represent some 93% of British miners' lamps in use, and this proportion is still increasing. The number of oil lamps, which has been falling for years, appears now to have reached a basic minimum.

(4.3.1) Electric Hand-Lamps.

All miners' electric hand-lamps consist basically of two parts—the lighting unit, containing a contact assembly and a well glass surrounding the bulb (usually protected with steel pillars and

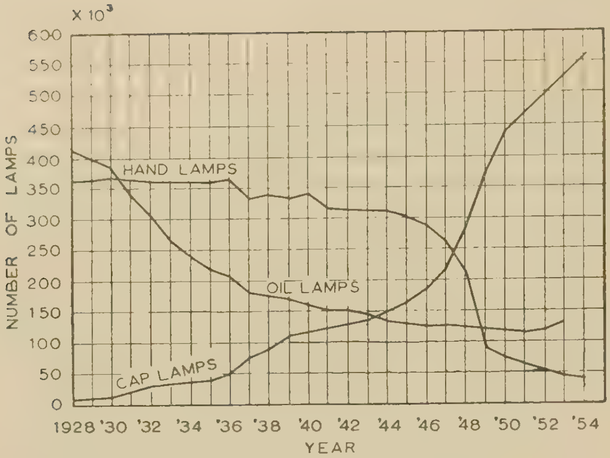

Fig. 1.—Growth of use of cap lamps in British mines.

provided with a hook) and the battery, which may or may not require an outer case.

Two types of accumulator are normally used, namely the lead-acid and the alkaline. In hand lamps using lead-acid batteries the cells are often contained in celluloid cases, which in turn are housed in an outer steel case. The latter may be closed at the base by a screwed plate secured by a magnetic lock.

In miners' hand-lamps with alkaline batteries the batteries are 2-cell units, each cell separately housed in a steel container, the mid-voltage point being connected to the outer casing.

(4.3.2) **Lead-Acid Batteries for Hand Lamps.**

Lead-acid batteries used in miners' hand lamps follow conventional lines. The positive group may be flat or tubular, the active material carried in a grid composed of an antimony–lead alloy or in a number of hard-rubber tubes. The negative plates are of normal grid construction. The electrolyte is a solution of sulphuric acid in distilled water and has a specific gravity of 1·250 when the battery is fully charged. The requisite 4 volts is obtained by employing two cells in series arranged side by side in a 2-compartment container. Lead-acid batteries for hand lamps are relatively cheap and easy to replate—a process which is usually performed by the lamp-room personnel.

(4.3.3) **Alkaline Batteries for Hand Lamps.**

In alkaline batteries the supporting medium for the plates is steel or nickel, the active materials being nickel peroxide in the positive plates, with iron, cadmium or a mixture of iron and cadmium in the negative plates. The electrolyte is a solution of potassium hydroxide in water, the specific gravity ranging from 1·19 to 1·21 according to the type of cell.

Alkaline batteries for hand lamps have a long life compared with their lead-acid equivalents, but they are relatively expensive in first cost and also for replatal. They can withstand considerable adverse treatment, including being left for long periods in a discharged state, but they may be heavier than lead-acid batteries of equivalent capacity.

(4.3.4) **Charging of Hand-Lamp Batteries.**

All miners' hand-lamp batteries must be removed from the lamps for charging. They are almost invariably charged at a constant current for a period determined by the time for which they have been in use. A number of batteries are connected in series on special charging frames, each circuit operating at 110 or 220 volts. The direct current required is obtained from the normal a.c. supply by motor-generator sets or transformer-rectifier units. Cut-outs or blocking rectifiers are used to preve any feedback from the batteries.

(4.3.5) **Electric Cap-Lamps.**

Cap lamps are constructed with the bulb carried in a hea piece affixed to the user's helmet, while the battery, supported b a belt, is carried on the miner's back. Headpieces are of plast or metal, and bulb and reflector assemblies are of similar desig in all types. Features of the newer models are their compactne and light weight. It is important that the weight should be sma and the centre of gravity should be as near to the helmet fixin as possible.

The lens glasses are of armoured glass approved by th Ministry of Fuel and Power, and they must carry an appropria marking. Lens rings are of metal or plastic and screw or cl into position.

Reflectors are generally of anodized aluminium, althoug treated plastic reflectors are also in use. The shape of th reflector is approximately parabolic and the light distribution determined by the degree of matting of the reflector surfac Generally, a semi-matt finish having a reflector ratio of 25 : is deemed suitable for the ordinary workman, but polishe reflectors with ratios of 50 or 100 : 1 are in use for officials an specialized tradesmen and are increasingly used by men engage in mechanical mining operations.

Main bulbs used in cap lamps may have either single or doub filaments, and are filled with krypton; the light output is abo 40 lumens. Some cap-lamp headpieces include a small auxili bulb having a lower current rating than the main bulb, which ac as a standby in case of failure of the main filament and can used to conserve the charge of the battery in an emergenc Alternatively, the auxiliary filament may be included in the ma bulb, but it is generally accepted that a second filament is advisab A switch is usually incorporated in the headpiece, to select t main or pilot filament or the 'off' position.

The headpiece must be locked against unauthorized openi by a magnetic lock, lead seal or special shrouded screw cover with a wax seal. The headpiece is connected to the battery a cable of specified design (see Section 4.7). The characterist of the cable are important, since the performance and the safe of the lamps are dependent upon it. Manufacturers now produ very satisfactory cable which has an average life of 2–3 yea dependent upon the severity of the conditions of its use. T cable is secured to the headpiece and battery in a variety of wa in different lamps, but in all cases the arrangement must strong enough to withstand a steady pull of 45 lb.

(4.3.6) **Lead-Acid Batteries for Cap Lamps.**

The lead-acid batteries used with cap lamps are of two typ differing principally in the design of the positive plates. O type of battery has tubular positive plates in which the act material is packed around lead splines and retained by slott rubber tubes. The other type employs flat positive plates of t pasted-grid type. The negative plates in both batteries are fl the grids being in the form of a lattice. The separators are hig absorbent, so that there is little free acid in the battery. T latter feature, coupled with a special venting arrangeme provides an unspillable battery which 'breathes' to atmosphe It is possible to charge such batteries without dismantl the lamps.

The groups are housed in a hard-rubber box which constitu the outer container. Topping-up with distilled water is acco plished by removing a filler plug and gasket on the side of battery, which uncovers two holes giving access to the two ce

* The reflection ratio of a cap-lamp reflector is the ratio of the maximum can power of the beam (usually at or near the centre) to the average candle-power over solid illuminated angle.

A typical discharge curve for a 4-volt lead-acid cap-lamp battery, supplying a bulb with a nominal current of 0·8 amp, is shown in Fig. 2. The normal working shift is about 8 hours, so that it will be seen that such a battery has an ample margin of capacity.

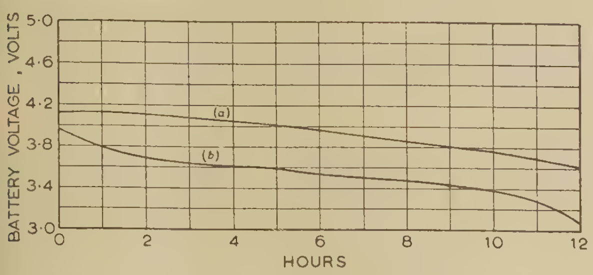

Fig. 2.—Voltage discharge curves of batteries.

(*a*) Lead-acid battery discharging through 0·8 amp (rating) bulb.
(*b*) Nickel–cadmium battery discharging through 1·0 amp (rating) bulb.

Battery covers are secured in a relatively permanent manner, usually by special shrouded screws with wax seals, since it is necessary to remove such covers only every 3–6 months.

(4.3.7) **Alkaline Batteries for Cap Lamps.**

The alkaline batteries used in British cap-lamps to-day are usually of the 3-cell type. Two makes of cap lamp incorporate 4-cell batteries, but they are not widely used in this country. The cells are of the nickel–cadmium and nickel–iron types, the groups and electrolyte being carried in steel containers sheathed in rubber sacks. The three cells are connected in series and housed in an outer steel container. The plates may be of either the pencil type, in which the active material is carried in a number of pencil-like tubes, or flat, with strip pockets to contain the active material.

A typical discharge curve for an alkaline cap-lamp battery is shown in Fig. 2. The load applied is the normal current of the appropriate bulb, namely 1 amp. Again it will be seen that the discharge period can be considerably longer than a normal working shift of some 8 hours.

The battery cover houses the contacts, a fuse, a cable lock, the gassing vents and filler holes. The gassing vents are normally closed during discharge, so that the cover, usually secured with a magnetic lock, must be removed for charging.

(4.3.8) **Charging Lead-Acid Batteries for Cap Lamps.**

Lead-acid cap-lamp batteries are invariably charged in parallel on a modified constant-voltage system, the low-voltage d.c. power necessary (at about 5–6 volts) being obtained from a transformer-rectifier unit. The circuit diagram for a typical unit is given in Fig. 3. Adjustment of the output voltage to suit variations in mains voltage or load current is achieved by tappings on the transformer primary. The voltage applied to the batteries with this system of charging is critical to about ± 100 mV; any larger variation may cause an excessive total charge with consequent shorter battery life, or may result in the battery not receiving a complete charge. The taper charge, which is controlled by the balance between the frame voltage and the battery e.m.f., should be such that when the battery is fully charged a small residual current flows into the battery. Such an arrangement is fundamentally necessary for a full self-service lamp-room system.

Various methods have been adopted to connect the lamps to the charging circuit, all of which must allow the lamps to be perfectly safe against open sparking in normal usage. The first

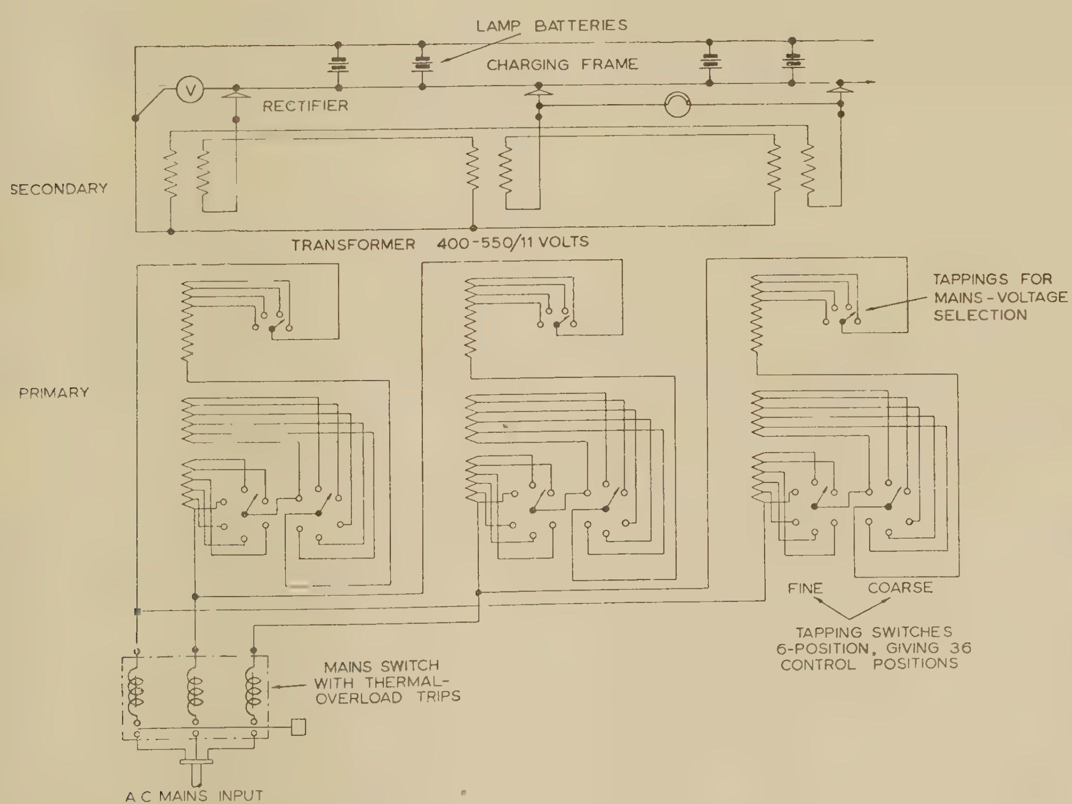

Fig. 3.—Charging plant for lead-acid cap-lamp batteries.

is a mechanical switching arrangement with one live contact on the exterior of the headpiece and the other obscured by a lock barrel which is turned by a live key on the charging frame to form the negative feed to the battery. A second mechanical device operates on the principle of a telephone jack-plug; the socket arrangement offers obscured contacts on the battery cover and the plug is on the charging frame.

A further arrangement for charging has two contacts on the exterior of the lamp. One of these is always live and the other is connected to the battery through a small metal rectifier, which allows the charging current to flow into the battery but blocks any return flow which might be dangerous. In one make of lamp the rectifier is housed behind the reflector in the headpiece, and serves also to convert the single-phase power into the d.c. power necessary for charging. Another make has the rectifier housed under the battery cover.

(4.3.9) Charging Alkaline Cap-Lamp Batteries.

Charging of alkaline cap-lamp batteries as used in this country is by constant current, numbers of the batteries being connected in series. The charging current is prescribed by the manufacturers, and the period of charge is related to the number of hours which the lamp has been in use. The charging stands are so arranged that they can be fed with direct current, which may be at 110 volts or 220 volts. In older installations, the direct-current supply is obtained from motor-generator sets, but in modern plants mercury-arc rectifiers are used.

(4.3.10) Self-Service.

The l.v. constant-voltage charging employed with lead-acid batteries permits the use of the so-called 'self-service' system of lamp-room organization, in which the user himself puts his lamp on charge and removes it from the rack again when proceeding to work. A typical layout for a lamp-room of this type is shown in Fig. 4. The route followed by the men is indicated, and it will be noted that provision is made for a one-way-traffic system, which is advisable to avoid congestion when large numbers of men have to pass through the lamp-room at the same time. The advantages of the self-service system may be summarized as follows:

(*a*) The lamps require a minimum amount of handling, whi results in a saving in labour and in less damage to equipment, pa ticularly to bulbs. The lamp-room personnel are able to devo themselves to the important operations necessary to maintain a hi safety and lighting standard.

(*b*) The men do not have to queue, which results in more order conduct at change of shift times.

(*c*) Each man has his own lamp and puts it on charge; he th takes a greater interest in it, which results in better maintenan and less damage.

(*d*) The size of lamp-room required for self-service is less than f hand issue.

(4.3.11) Self-Help Arrangements.

A modified form of self-service sometimes termed 'self-hel is used in some lamp-rooms with lamps having alkaline batteri In this system the men enter the lamp-room and place th lamps in convenient storage racks from which the attendan remove the lamps or batteries for charging, replacing them befo they are required for use again. Such a system differs from t self-service scheme for cap lamps with lead-acid batteri because, in general, alkaline batteries are not charged at consta voltage and the lamps must be opened before the batteries ca be put on charge. A typical self-help layout is shown in Fig.

(4.3.12) Maintenance of Miners' Lamps.

It is pointless devoting considerable effort to improving lam design unless full advantage is taken of such improvements keeping the lamps in the best workable condition day by da Serviceability is influenced by design factors, but good mai tenance basically depends upon the ability and keenness of t personnel in the lamp-room. Obviously, training can play predominant part here, and it is pleasing to note that instructio courses for lamp-room employees are being arranged in ma parts of the country.

Good maintenance can be best effected by the employment a senior official having charge of a group of installations such those constituting a National Coal Board Area. Such an offic can devote himself entirely to the maintenance of high standa of safety and light output by regular supervision of each instal tion, the keeping of suitable records and close co-operation w the manufacturers of the equipment in use. He can thus ens

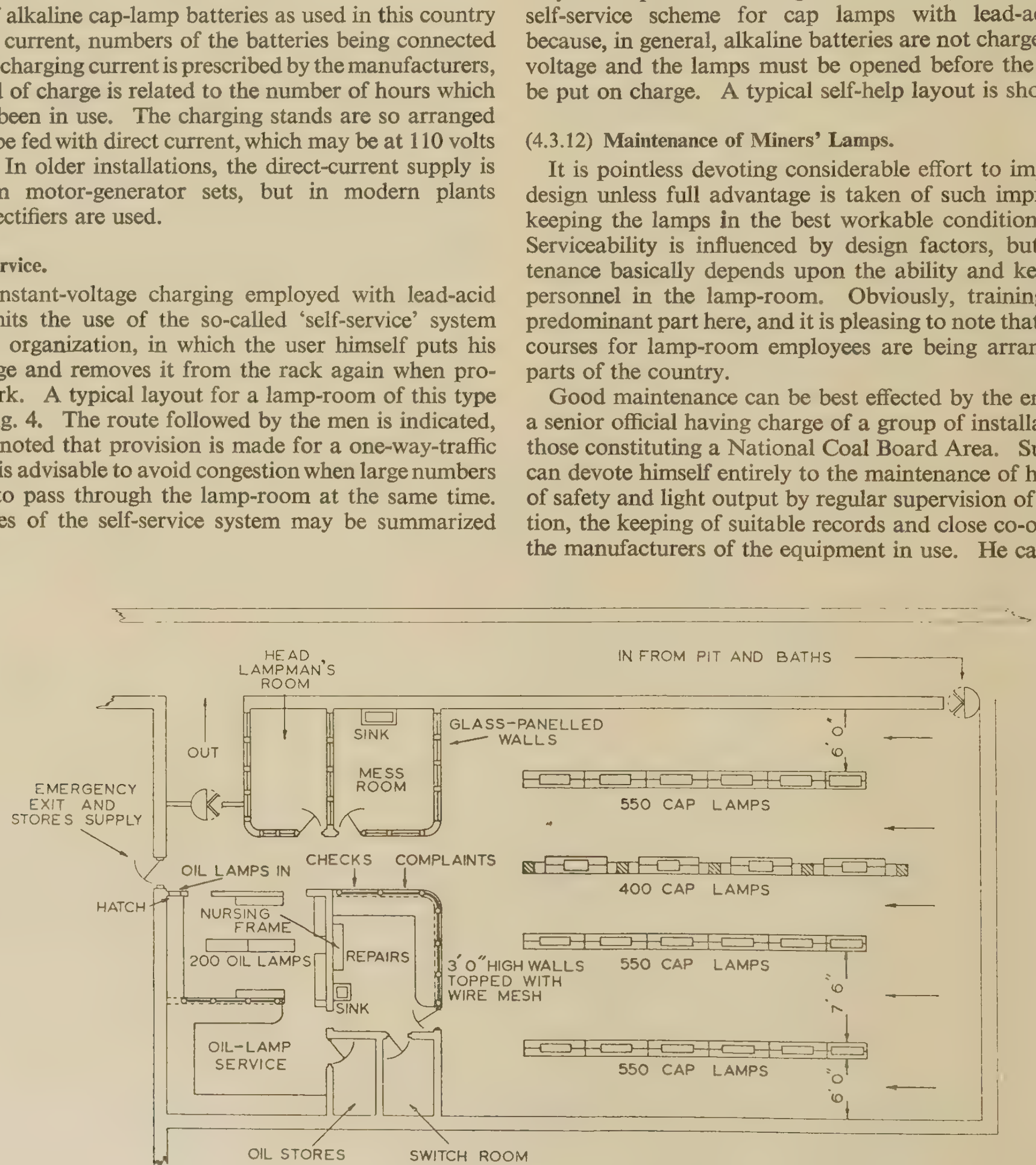

Fig. 4.—Lamp-room layout for the self-service of 2050 lead-acid-battery cap lamps and 200 oil lamps.

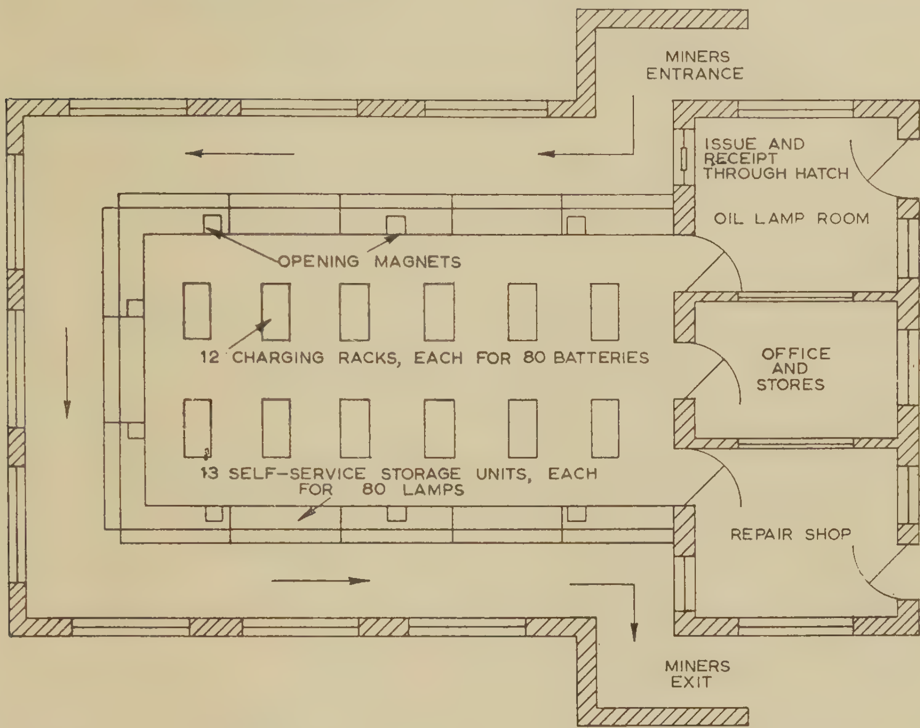

Fig. 5.—Lamp-room layout for the self-issue of 1 040 alkaline-battery cap lamps.

that the best practices are adopted at all the installations under his control.

(4.3.13) **Relative Performance of Miners' Lamps.**

Through the attention devoted to the design of batteries, bulbs and switch contacts and to reflector finish, etc., the performance of miners' cap-lamps has steadily improved, particularly in the last 10 years or so.

The best method of assessing the efficiency of a cap lamp as a light-producing medium is to consider its light-output/weight ratio, i.e. the ratio of the light output from the lamp at the end of a 9-hour shift (the Ministry of Fuel and Power approval figure) to the weight of the complete lamp. In 1934 the average ratio was approximately 2 lm/lb for cap lamps and 2·6 lm/lb for hand lamps. These ratios have increased until at the present time they are approximately 6 lm/lb for cap lamps and 5·7 lm/lb for hand lamps. There has thus been a very considerable improvement in cap-lamp performance recently and, short of some radical new departure in, say, battery technique, it would appear to be difficult to improve the efficiencies to any great extent.

(4.4) Lamp-Room Photometry

The advent of the 1947 Lighting Regulations encouraged the wide application of photometers in lamp-rooms, and to-day an installation without such an instrument is an exception. A photometer is essential for the efficient operation of any sizeable lamp-room.

The instruments used are of two types, one measuring the mean spherical candle-power of cap lamps and the other the maximum horizontal candle-power of hand lamps, these two values being taken as bases for comparison of performance. Both instruments incorporate a selenium photocell, the current from which is measured by a microammeter calibrated for direct readings of candle-power. With the cap-lamp photometer the total light emitted is integrated in a cube or sphere, whereas the directional light in the hand-lamp photometer is measured by a cell at the end of a felt-lined brass tube.

The testing of the lamps in the lamp-room is carried out to a carefully planned system. It is usual to test all lamps once a month, a fixed number being tested each working day or during the week-ends. The Regulations require a prescribed percentage maintenance in relation to the approval value of the lamp in question, but a somewhat higher figure is generally selected as the minimum acceptable.

The inauguration of such systems of photometric control has had a salutary effect upon lamp-room maintenance standards, and where regular tests are carried out and the appropriate deficiencies rectified, very few installations fall below the statutory requirements.

(4.5) Legislation relating to Portable Lighting

The first legislation concerning the provision of adequate illumination in mines was introduced in 1913[1] and laid down a standard for miners' lamps. No further legal requirements were published until the Regulations in 1934,[2] which improved somewhat the very low standards required by the 1913 Code. New minimum approval standards of candle-power were introduced, and an attempt was made to acquire a reasonable standard of maintenance. This latter requirement was extremely vague and could not be implemented effectively.

Progress in lamp design made it possible to demand improved performance in the Regulations issued in 1947.[10] These aimed at improving the standard of new lamps approved by the Ministry of Fuel and Power and the enforcement of the maintenance standards generally accepted in well-run lamp-rooms.

In these considerations the most important of the requirements of the 1947 Regulations are those referring to the minimum standards of performance of cap lamps, since these concern the lamps most generally used to-day. The minimum mean spherical candle-power at the end of a 9-hour discharge which will be

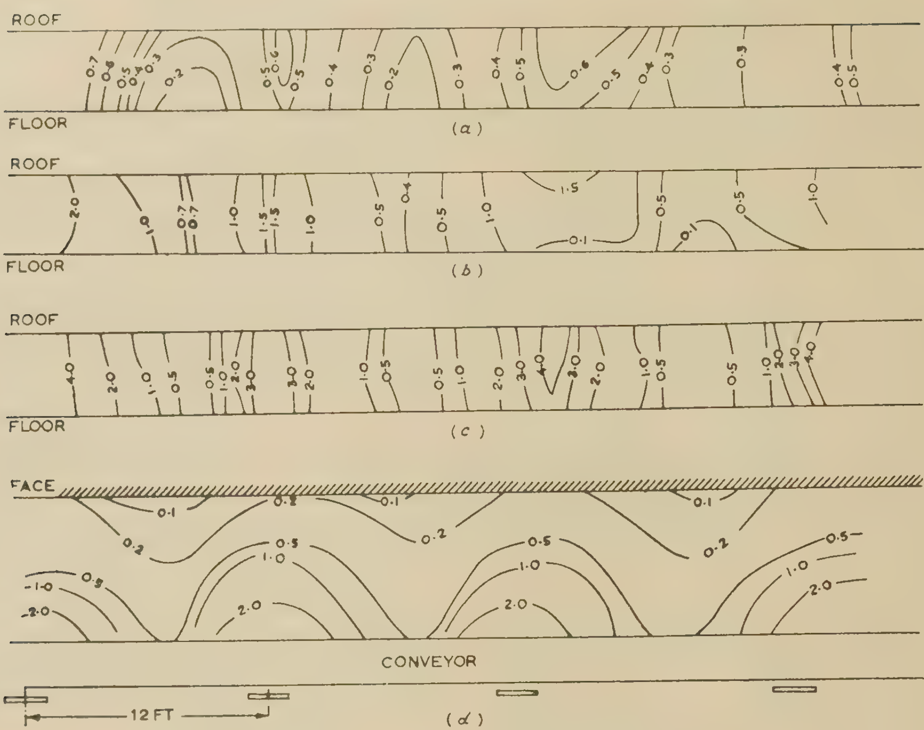

Fig. 6.—Results of a coal-face illumination survey at a colliery using 40-watt 2ft fluorescent fittings.

The figures give the illumination in lumens per square foot.
(*a*) Vertical face 9ft from lamps.
(*b*) Vertical face 6ft from lamps.
(*c*) Vertical face 3ft from lamps.
(*d*) Horizontal plane at floor level.

accepted for the type approval of a cap-lamp to-day is 1·20 when krypton-filled bulbs are used. This figure is well exceeded in practice, for approval figures range from 1·46 to 2·20m.s.c.p.

The requirements regarding maintenance are now such that lamps must be so maintained that, when tested to a prescribed schedule, 50% must show a certain proportion of the approval standard fixed for the type of lamp involved. The proportion of the approval standard at present required is 60%, which can be increased, if desired by the Ministry of Fuel and Power, to a maximum of 75%. A 60% maintenance figure is not difficult to achieve when reasonable care is practised in the lamp-room and systematic photometric testing is carried out.

These requirements mean that for the first time a workable arrangement for ensuring a satisfactory maintenance of portable lamps has been instituted and there has been a subsequent marked improvement in lamp-room practice throughout the country.

(4.6) Miner's Lamp Bulbs

One of the most vital parts of a miner's lamp is the bulb. In recent years, much attention has been devoted to the design of such bulbs and three important advances have been made, namely the use of krypton for filling, the shortening of the nominal life and a reduction in the variety of types in use. Krypton-filled bulbs have a lumens-per-watt efficiency some 15–20% higher than the equivalent argon-filled bulbs used previously, but owing to the relatively expensive nature of the gas, the envelopes must be kept as small as possible. The bulbs generally used to-day have an 18mm glass envelope and a cap with a miniature Edison thread. The small size of the bulbs makes their production to close limits difficult—a factor which has recently influenced cap-lamp design. It is difficult to obtain a consistently good light distribution with the relatively wi tolerances prescribed for the bulb light-centre length, so th cap lamps are now being produced with a focusing arrangeme The ratings in most general use are 4 volt 0·8amp or 4 vo 1amp for cap lamps with lead-acid batteries, and 3·75 vo 1amp for cap lamps with alkaline batteries.

Until recently the bench life of miner's-lamp bulbs was 400 500 hours, but this has been reduced to 200 hours for cap lamp and 250 hours for hand lamps, allowing a materially increase light output. This change has involved higher operating cost but these are considered to be well worth while.

Owing to the voltage drop in the cable and the falling volta of the battery during discharge, cap-lamp bulbs operate bel the nominal rated voltage for a large proportion of their worki life. This has the effect of lengthening the actual life of su bulbs to some two and a half to three times the bench life.

The reduction in life and the introduction of krypton filli coupled with other improvements in technique, have resulted an increase of 30% in the luminous output of such bulbs for t same power consumption.

The increase in light output from miners' cap-lamps accentuat the glare effect experienced by other persons in the vicinity the wearer. Attention is therefore being devoted to the possibi of reducing this glare, and probably the most promising modific tion is the partial frosting of the bulbs so that the filament its is not directly visible.

For a number of years, numerous types of bulb were in use miners' lamps, but this position has now been improved material A list of agreed mining bulbs drawn up by the interested part includes 29 types, and since a number of these are used in lam which are obsolescent, there will be fewer in the future.

The revision of B.S. 535: 1953 covers only those bulbs

general use in the industry. However, it is intended that as other bulbs come into general use they will also be covered by the Standard.

(4.7) Cables for Miners' Cap-Lamps

It is apparent that the cables used with miners' cap-lamps should conform to very close standards. Accordingly, B.S. 937 was published in 1937, and is at present being revised in the light of experience.

In order to achieve maximum safety and efficiency of performance a cap-lamp cable should have the following features: It should be highly resistant to abrasion or damage by tension, but it must also be flexible and the conductors shall not fracture on repeated bending; the sheath must be resistant to deterioration by contact with oil, grease or body fats, and it must not burn readily; the electrical conductance must naturally be as high as possible without the cable being too bulky.

The cable generally used to-day has two cores each made up of 40 annealed tinned-copper wires having an individual diameter of 0·0076 in and insulated with a pure rubber sheath 0·02 in thick. The two cores are laid up in a close spiral round a non-inflammable strain cord and surrounded by a sheath of polychloroprene compound to a thickness of 0·04 in. The overall diameter must be 0·345 in $\pm$ 0·01 in.

(5) MAINS LIGHTING UNDERGROUND

The light output from portable lamps is restricted by the weight of the batteries from which they derive their power. Since the battery weight is about the maximum tolerable, it is obvious that mains power will be needed if lighting underground is to be improved materially. Such lighting has, in fact, been in use underground for a number of years, the first such installation being at Earnock Colliery, Lanarkshire, in 1881. Early installations were similar to those used on the surface, but specialized designs have been developed for mining use through various stages to the modern flameproof equipment available to-day. The first mains lighting was around the shaft bottom, from whence it has gradually extended to the main roadways, engine houses, junctions and ultimately, although to a restricted extent, to the coal-face.

(5.1) Legislation relating to Mains Lighting

Under the latest Regulations, mains lighting below ground is permitted on intake airway roads except within 50 yd of the coal-face, and on other roadways except within 300 yd of the face. Furthermore, if electricity is permitted in a district, mains lighting can be used except within 10 yd of the face on intake roads and within 100 yd of the face on other roads, or except within 10 yd of the face in any circumstances if specially authorized by the Inspector of the Division. It can be used in any place in a mine if the Regulations of the Mine permit, which means, of course, that special regulations may be involved.

The voltage of an underground lighting system may not exceed 250 volts, and the neutral point of a polyphase system or the mid-point of any other system is required to be earthed.

Appropriate precautions have to be taken to protect lighting equipment from damage due to shot-firing, and the fittings must be so designed as to protect the lamps from accidental damage.

The Regulations also prescribe that all important places in the mine, where the concentration of workmen, density of traffic or presence of machinery require it, shall be effectively whitened where this is reasonably practicable, and general lighting shall also be provided at such places. The actual form of this general lighting is not specified, but portable lighting may not be considered adequate at certain strategic places. It is necessary in all circumstances for every person to be provided with a portable electric lamp for emergency purposes.

All new lighting equipment for use within 300 yd of the coal-face must be of a type approved by the Ministry of Fuel and Power.

(5.2.1) Roadway Lighting.

It is estimated that there are some 14 000 miles of underground roadways in British collieries along which men ordinarily travel, and the problem of lighting sufficient of these adequately and evenly is by no means easy of solution. It is doubtful whether the best arrangement has yet been found, although much progress has been made in recent months. In the long low tunnels, where general lighting is required, it is difficult to provide enough light without producing pools of contrasting light and dark, and to ensure absence of glare. At the best, some compromise has to be made. Where specific work is performed at junctions, loading points and pit bottoms and where tubs are to be lockered, attached together or to a haulage rope or locomotive, the lighting must be such that the operator does not stand in his own light and that deep shadows are not cast, the effect of which may be more marked in a place which is otherwise generally well lit. Much useful photometric work has been done to ascertain the requirements for even and adequate illumination at such working points, but it is certain that many accidents could be avoided by more attention to such lighting. The importance of this localized lighting is appreciated by the authorities, as it is now obligatory for all haulage hands to carry cap lamps.

Fixed fittings for roadway lighting may be spaced according to requirements. A wider distribution is adopted for those places where the personnel merely pass along a roadway and do not perform work there.

There are two principal types of tungsten-filament-lamp fittings in use, namely the well-glass and the prismatic types, both being flameproof and connected together by armoured cable.

The standard version of the well-glass fitting is arranged for attachment to the roof of a roadway and has a clear-armour-plate well glass; frosted glasses are available but are not accepted as flameproof. The fitting with a prismatic glass is designed for wall mounting generally and gives a wide distribution of light without glare. The surface brightness is materially reduced by the shape of the glass. This unit is perhaps the best for use in roadways where the height is restricted and where reduction of glare is an important factor.

A recent careful investigation correlating preliminary laboratory work on scale models with later experiments in roadways below ground has resulted in the development of a new type of well-glass fitting which materially reduces the glare in roadway lighting. This fitting, which is flameproof, incorporates an additional interior refractor glass which improves the light distribution; it reduces the light intensity along the length of the mine roadway, i.e. the line of the observer's vision, and increases the illumination of adjacent walls, so reducing the contrast.

The recent introduction of fluorescent discharge tubes underground represents an outstanding advance in lighting technique. The application of this form of lighting, which is widely used in surface offices, workshops and streets, is a logical development in mine lighting. The advantages are low power consumption per unit of light output, freedom from glare and after-image, less shadow and a more even light distribution.

A typical fluorescent fitting for roadway use includes a body of aluminium alloy with end-castings which form the housings of a transparent protective cylinder surrounding the fluorescent tube. The control gear is included in the fitting, and cable entry may be from one or both ends. Three sizes are available for 20-watt 24 in, 40-watt 48 in and 80-watt 60 in tubes. Safety

switches were included, at one time, which were closed by the insertion of the tube and opened automatically if the tube was broken. Such switches are no longer generally used as they proved troublesome.

The cost of applying and maintaining fluorescent systems for roadway lighting has not yet received very much publicity; the capital outlay is higher than for tungsten-filament lamps, but the operating costs may be lower.

(5.2.2) Distribution of Electricity to Roadway Lighting Systems.

The permissible maximum voltage for mains lighting below ground was increased from 125 to 250 volts by the 1947 Lighting Regulations, but owing to the relatively long transmission distances, power ultimately used for lighting is distributed at high or medium voltages. Thus it is necessary to transform down to the lower voltage at or near the actual lighting points. In the vicinity of the pit bottom, where large numbers of lights are situated, transformers of 5–10 kVA capacity are situated in the main substations.

The lighting circuits, consisting of lighting fittings supplied generally by wire-armoured cable, are controlled by suitable switchgear in the main substation. Local switches are also used where the lighting fittings are situated some distance from the substation.

For use inbye (i.e. situations relatively remote from the pit bottom) small lighting transformers, generally covered by a flameproof certificate, are installed at suitable places so that lighting is available where required. Thus, distribution at the low lighting voltage is reduced to a minimum. Armoured cable is invariably used for connecting lighting systems inbye.

(5.2.3) Flameproofness.

It is not essential that all mains lighting equipment in use underground should be flameproof, and it is considered by some engineers that there are situations where industrial types of equipment are quite adequate. It is suggested that, after the allowance of an ample margin for the possibility of the firedamp content rising above that normally experienced, there is no need to establish rules more stringent than statutory requirements which specify where the flameproof equipment should be used. Flameproof lighting fittings are costly, their weight and bulk are considerable and their construction sometimes restricts the light distribution. It is claimed further that, if the full benefit of roadway lighting is to be obtained, the wide application of the use of flameproof fittings is ruled out on economic grounds alone. In practice, many mining electrical engineers insist on flameproof lighting equipment below ground to avoid the risk of units being wrongly used in dangerous situations.

The requirements with regard to the places where flameproof equipment has to be used may be changed by new legislation in the near future.

(5.2.4) Suggested Standards of Lighting for Mine Roadways.

The difficulties associated with the provision of adequate lighting on roadways underground mean that in many circumstances standards of illumination have to be accepted inferior to those which might be demanded on the surface.

The following standards of illumination have been suggested as possible for mine roadways: [24, 45]

	lm/ft^2
Areas in and around the shaft bottom	6–10
Main junctions, loading points and stations for man-riding trains	4–6
Other illuminated roadways below ground ..	0·2–0·4

These values, particularly the last one, will certainly seem to surface lighting engineers to be very low, but even so they are difficult to achieve in mines. Much can be done to assist in improving illumination by regular attention to the whitening of the sides and roof of the roadways involved. This will also reduce the discomfort and glare from the lighting fittings used, since it will reduce the contrast between the brightness of the light source and the surrounding background.

(5.3.1) Face Lighting.

The lighting of the coal-face is perhaps the most difficult problem of all. The space is even more restricted than on roadways, and light distribution is impeded by roof supports and machinery. Furthermore, the position of the face is transient, in that it moves forward, usually daily, as the coal is extracted, rendering whitewashing impracticable. The presence of machinery in the confined space of the working place, and the necessity for continual observation of the roof over the face require good lighting if accidents are to be minimized and output is to be maintained at the highest level. Furthermore, the rigorous conditions associated with coal production, including shot-firing, call for extremely robust equipment which must also be light in weight, for it has to be moved frequently.

The increased amount of light which can be made available with the unlimited power supply from the mains, compared with the limited illumination from portable lamps, makes such systems very attractive. Mains flood-lighting on the face has been widely used in Germany for a number of years, and had it not been for the 1939–45 War, its use would have been even more extensive. The successful application of coal-face mains lighting in Germany may be attributed largely to the relatively rare use of shot-firing, the coals being generally much softer than ours.

In Great Britain, experiments with mains lighting at the face have been tried at intervals since 1881, but the first serious attempt with modern equipment was at Birch Coppice Colliery, Warwickshire, in 1927. Unfortunately, these trials and others in succeeding years were ultimately abandoned, owing to the high maintenance costs and the difficulty of proving that the venture was an economic success. Unless it was possible to show financial saving through increased production or a reduction in the accident rate, mining engineers were hesitant to introduce a new system which meant a definite increase in cost.

Further sporadic trials were carried out in Great Britain in the intervening years, utilizing many new ideas for increased safety. Between 1931 and 1935, the Safety in Mines Research Board carried out certain experiments both in the laboratory and underground, using bulbs and well-glasses with special pressure-operated cut-outs and fillings of inert gas. Owing to the additional complications involved and the relative unreliability of the devices employed, the experiments were abandoned.

(5.3.2) Fluorescent Lighting on the Coal-face.

It was the development of the fluorescent tube for industrial use and its advent in small sizes that stimulated the official interest of the National Coal Board in the matter and opened up a new field of investigation in connection with flood-lighting in coal mines. The low intrinsic brilliance and large area of light source provided by fluorescent tubes make them particularly suitable for lighting the confined spaces encountered on the coal-face, since they do not produce glare or harsh shadows.

Since 1948 experimental installations of face-lighting equipments have been installed at collieries in various parts of the country, the experiments being under the supervision of the lighting engineers of the National Coal Board.[26] In general these experiments were concerned with fluorescent-tube install

tions, although latterly attention has been paid to fittings incorporating filament lamps.

Two types of fluorescent-tube fitting have been employed, both of which are approved. One unit gives an almost all-round light and the other has a directional light distribution. A unit of the first type is constructed of a cast aluminium alloy with a Perspex guard for the tube, which in turn is protected by a stout wire cage. The length of the unit is 28 in, the width is 7 in and the depth 8 in; 18 in tubes of either 15 or 30 watts are used, singly or in pairs operating at 125 volts, the weight of the unit being about 23 lb. When spaced at intervals of 4–5 yd over the face conveyor in a seam 5 ft 6 in thick, the double-tube fittings give excellent results, the illumination being sufficient for working under difficult mining conditions.

Results of an illumination survey on a coal-face lighted with 40-watt fluorescent fittings including 2 ft tubes spaced at intervals of 12 ft are shown as contours in Fig. 6. It will be seen that a large proportion of this face was lighted to the minimum standard of illumination of $0{\cdot}4\,\mathrm{lm/ft^2}$ set out as an objective in Section 3. It has been reported that the experiments have indicated that mains lighting under suitable face conditions is a practical proposition.

Another development in fluorescent-tube fittings for mining use incorporates a circular tube of 10 in diameter having a power consumption of 40 watts. Behind the tube is an anodized-aluminium reflector giving a wide light distribution. The fittings are usually mounted vertically and incorporate dome-fronted glasses. The auxiliary gear, which includes an instant-start arrangement, is incorporated in the fittings. Installations of such fittings have proved very satisfactory on both roadways and faces in mines in the north of England.

(5.3.3) Tungsten-Filament Lighting on the Coal-Face.

An installation of tungsten-filament-lamp face lighting at a West Midland colliery employs 60-watt fittings constructed to give a directional illumination. The surface brightness is reduced to half that of a fluorescent tube by an external opalized dome of acrylic plastic. Illumination surveys have indicated that the coal-face illumination values obtained with these fittings are similar to those with fluorescent tubes, but a closer spacing of the lamps is necessary to obtain equivalent lighting values. Such fittings are lighter in weight, less bulky and cheaper than their fluorescent counterparts.

One of the disadvantages of a mains-lighting installation on the coal-face is that it has to be advanced as the face moves forward, which has hitherto proved to be an inconvenient and costly procedure. With the introduction of armoured conveyors onto some coal-faces in Great Britain, which are not dismantled but are pushed forward intact by pneumatic or hydraulic rams, it is possible to mount the lighting fittings on the back of the conveyor so that they move forward with it. A disadvantage of this arrangement is that the placing of the fittings is such that they are frequently in the line of vision of workers on the face and it is difficult to avoid undue glare. A sketch of the arrangement for mounting fittings on an armoured conveyor is shown in Fig. 7.

(5.3.4) Power Supply for Face Lighting.

The single-phase supply for mains lighting on the face is obtained from flameproof transformer-switch units made in the form of a gate-end box. The fittings are connected to the pliable armoured cable by 4-pin plug-and-socket connectors, which enables the equipment to be dismantled easily and facilitates its daily advance as required. The 4-core cable includes two power cores, an earth core and a pilot core. The latter carries a pilot current which serves to operate the contactor in the gate-end

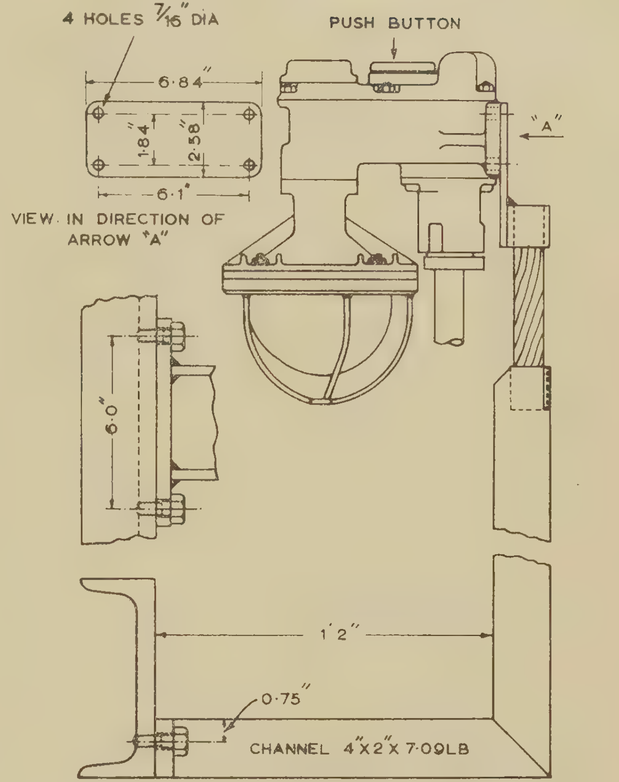

Fig. 7.—Semi-permanent face-lighting and signalling unit mounted on conveyor.

switch unit and to break the circuit if the earth or pilot cores are interrupted.

(5.3.5) Face Signalling by Interruption of Lighting Systems.

A further advantage of certain systems of mains lighting is that they can be used to provide an efficient means of visual signalling. Thus it can be arranged for machinery to be stopped in an emergency by signalling from any of the lighting units along the length of the coal face. Furthermore, an operator can signal clearly before restarting the conveyor. Thus visual signalling provides additional safeguards for the personnel working on the face.

The switching of the lights in one system is achieved by push-button switches built into the lighting fittings. The fittings are connected together by short lengths of 5-core cable plugged into the units along the face. The last lighting unit on the face is closed by a blanking plug containing a rectifier connected in the pilot circuit. The outgoing supply to the lamps is controlled through a contactor by an intrinsically safe circuit, made through the pilot and earth cores of the trailing cable. This circuit also guards against pilot-to-earth faults and offers earth-core continuity, the principle involved being shown in Fig. 8. Thus,

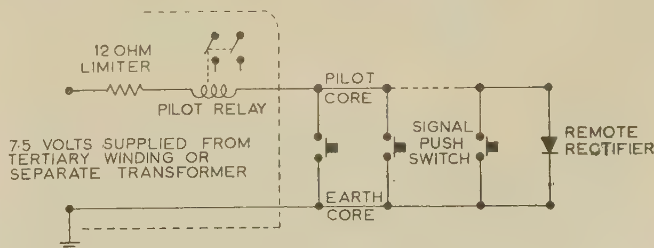

Fig. 8.—Pilot signalling circuit for mains lighting unit.

when one of the signalling switches is closed the remote half-wave rectifier is short-circuited, so that the pilot relay in the gate-end box receives alternating current. Since it holds in only with direct current, it opens and breaks the contactor-coil circuit, so interrupting the supply to the lamps. The supply remains off until the signal push button is released, when the lights are restored.

Provision can be made for audible signalling if this is required.

(5.3.6) **Safety and Economic Considerations of Face-Lighting Systems.**

The use of power-fed lighting fittings at the coal-face still presents an element of danger, both from the fittings themselves and from the cables used, but this has been reduced by recent developments, including special cut-out devices, inert-gas fillings and the use of cold-cathode tubes; a special investigation of this problem is at present being carried out.[36]

Unfortunately, at the present time, there is a ban on the introduction of equipment made of aluminium or aluminium alloys onto the coal-faces in British mines, since experiments have shown that firedamp-air mixtures can be ignited when apparatus made of aluminium or magnesium alloys is violently impacted with another object of iron or steel, particularly if the latter is rusty.[48] This restriction is limiting the development of the requisite equipment, for it is essential that the units should be light enough to be handled easily in the restricted spaces on the coal face. It is hoped that the difficulty will be overcome by the use of alternative materials and the redesign of the units where necessary.

As already mentioned, the economic aspect of coal-face lighting calls for serious consideration. It has been estimated that the cost of employing fluorescent mains lighting on the coal-face is between 2d. and just under 3d. per ton of coal produced, and the cost for incandescent-filament lighting somewhat less. Unfortunately, it has not been possible to put very much on the credit side against this increased cost, and consequently there is little enthusiasm in some circles for the widespread lighting of coal-faces in this country.

The results of the experiments carried out by the National Coal Board are as yet too limited for final conclusions to be reached regarding the overall suitability of mains lighting on the coal-face, but it is safe to say that such lighting provides a great improvement in working conditions and must also make for greater safety. It is reasonable to assume, however, that it will be some years before the use of such systems will be universal. In fact, in certain localities geological conditions are too adverse and some seams are too thin for mains face lighting to be a practical proposition.

(6) PNEUMATIC-ELECTRIC UNITS FOR LIGHTING UNDERGROUND

Pneumatic-electric units containing individual turbo-generators are useful for lighting those places in mines where compressed air is the only source of power available or where electricity cannot be used owing to danger of firedamp explosion. Such equipment has been in use in British coal mines for a number of years, and the number of all types had risen to over 5 000 at the middle of 1953.

The latest form of well-glass fitting incorporates a 40-watt mercury-discharge lamp having a life exceeding 4 000 hours, an approximate light output of 1 400 lumens and an air consumption of about 7 ft^3/min; such units are used largely on roadways at loading and transfer points. A more recent development is a unit including two 15-watt 18 in fluorescent tubes backed by reflectors, the power being produced by a turbo-alternator consuming air at about 6 ft^3/min; the light output is abou 1 200 lumens. Two installations of these fluorescent fitting have been tried on coal-faces in British collieries; the illuminatio values obtained were 0·75 lm/ft^2 opposite the fittings an 0·23 lm/ft^2 midway between, the lights being 12 ft from the fac and spaced 15 ft apart.

The capital outlay for a coal-face installation of pneumatic electric fluorescent lamps is somewhat less than that of a mains fed equivalent, but owing to the relative inefficiency of com pressed air, the cost of operation may be as much as one-thir higher. It has been demonstrated, however, that such installa tions can be operated satisfactorily where conditions warrant.

(7) CONCLUSION

Considerable progress has been made in mine-lighting tech nique in recent years, particularly in the standard of light outpu from the portable lamps in use. Further small increases i illumination from such units may be forthcoming as designs ar improved, but there is little chance of any major advance in thi respect unless some new fundamental principle is used. Th problem of maintenance has been tackled satisfactorily, and ver consistent results have been obtained where photometric contro is employed.

The latest regulations governing the use of mains lightin underground have made it possible to extend its applicatio Attention is being devoted to the efficient utilization of ligh below ground and to its even distribution, but much remains t be done in this direction. Certain recent developments in th design of lighting fittings minimizing glare and making th distribution more even offer promise.

On the coal-face, a few mains-lighting installations usin fluorescent tubes fed either from the mains or from compresse air-driven generators have been installed experimentally. I general, the results from these installations have been satisfactor but further developments are held up by the ban on the use o aluminium alloys on the coal-face. The economics of a genera introduction of mains lighting on coal-faces are still uncertai but there is no doubt that considerable benefits would accrue.

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DISCUSSION BEFORE THE UTILIZATION SECTION, 15TH MARCH, 1956

Mr. B. L. Metcalf: The present method of defining the properties of a cap-lamp reflector is based on the maximum candle-power compared with the average candle-power over the slope of the illuminated angle. A more appropriate means of defining this ratio might be to compare the maximum directional candle-power of the headpiece with that of the bare bulb. This would give a direct comparison in terms of a concentration ratio. For example, if the bulb in a reflector provided a maximum directional candle-power of 100 and the maximum candle-power of the bulb was 5, the ratio would be 20 : 1.

In Section 4.3.10 the author lists four advantages of the lead-acid-battery self-service system. Would these same advantages apply to the alkaline-battery self-help system? He mentions that in the self-help system for alkaline batteries the lamps have to be opened before the batteries can be put on charge. This may be a point in their favour, since it means that the internal contacts can be examined day by day and kept clean.

Maintenance of cap lamps is a vitally important factor; the requirements of the Ministry of Fuel and Power are that, when tested to a prescribed schedule, 50% of the lamps must show 60% of the approval standard—a figure to which we are now working. It could, of course, be improved, but one has to balance the advantages due to improved maintenance against the increased cost of achieving it.

In Section 4.6 the partial frosting of cap lamps is mentioned. Tests have been carried out at about 14 selected collieries to determine the user reaction to the tip-frosted cap-lamp bulb. The results of these tests have been very encouraging. Users report in general that the frosted bulb reduces intrinsic brightness of the source and provides a more diffused light. It is not intended that partially frosted bulbs should replace those with a clear envelope, but they will be available as an alternative.

On the general question of portable lamps, I should like the author's views as to the direction in which he thinks improvements will take place over the next few years and the prospects. Improving the light output is not the primary consideration. Attention should be directed towards improving the voltage maintenance and reducing the weight.

On coal-face lighting the paper does not stress sufficiently the difficulty encountered with aluminium alloys. It has been proved that two or three serious accidents have been caused by the impact of aluminium on rusty iron, and as a result the use of aluminium or aluminium alloys has been banned, with one or two exceptions, from the coal-face. This has put a complete stop at the moment to portable coal-face mains lighting, as there is no alternative fitting which is sufficiently light in weight to be handled. Until we get some suitable material we shall not be able to make progress. All kinds of alternatives have been considered. Plastic is one of them, but there is the difficulty of getting a flameproof joint in plastic which will not buckle under heat.

As the author says, it is very difficult to assess the advantages of coal-face lighting. It takes a long time to measure any reduction in the accident rate or in the improvement in output or reduction in dirt filled. These are very difficult quantities to measure, but undoubtedly good lighting should help in all these directions.

Figures are given in the paper for costs. The capital cost is

roughly £1 000 per 100 yd of coal-face for fluorescent lighting fittings. The running cost when using compressed-air-turbine fluorescent fittings is about 4d. per ton of coal produced on the same basis as the figures given by the author. On the same basis of calculation it would save ¾d. a ton if the fittings were mounted on the conveyer, since the fittings and the conveyer are moved forward together. Lighting fittings on conveyers and power loading machines would give lighting down the face without the bother of separate connections. More collaboration between the lighting-fitting and the machinery manufacturers would be an advantage.

The Germans use more complicated systems of signalling at the face than we do; but taking the country as a whole, the continual flickering of the lights is not popular. Our practice is to install sound power telephones and use the switching of the lights to call the man to the telephone.

I am glad the author referred to standardization. We have reduced the numbers of cap lamps from 45–50 types to seven basic types in B.S. 927, and we hope under the new revision of the cable specification to have one type of cap-lamp cable only.

The National Coal Board use about 2¼ million cap-lamp bulbs a year, and they have their own station at which batches of bulbs are tested, with the result that rejections have been reduced from 10% to 3%.

Dr. A. Roberts: Most cap lamps in use to-day have a light distribution which can provide 0·4 lm/ft^2 over a circle some 6 ft in diameter at a distance of 4 ft. This is substantially less than the visual field, and outside the central cone there is only an insignificant amount of light obtained by inter-reflection from the surroundings.

A miner operating a machine may require to fixate on objects at distances greater than 4 ft in an atmosphere thick with dust. He therefore prefers a polished reflector which concentrates the available light flux into a narrow beam. Although this may enable him to fixate at the distances involved, it reduces still further the effective cone of light distribution in circumstances where the proper functioning of peripheral vision is essential to safety. Accidents caused by contact with moving machinery show a trend of steady increase year by year.

It is therefore obvious that the cap lamp cannot by itself provide adequate lighting for all purposes. On the other hand, there appears to be little prospect of the general adoption of mains lighting at the coal-face.

It may be that in the years to come the problem of lighting the coal-face will solve itself, for machines need no light, and mine mechanization has reached a stage when we can look forward with reasonable hope to the day when the coal-face will be completely mechanized and operated by remote control.

In the meantime the problem remains with us and I should like to ask the author whether there is a field for semi-portable battery lamps which might be designed to give a light output comparable with mains lighting but which would be free from many of the disadvantages which mains fittings possess. By semi-portable I mean that the lamps would be removed from the coal-face to an underground charging station and then brought back and positioned at suitable places along it.

Prof. I. C. F. Statham: The author stresses the importance of mine lighting from the aspects of safety, health and production. With regard to safety, it may not be possible to assess accurately the effect of mine lighting, but it will be obvious that, at the coal-face in particular, sufficient illumination must be provided to enable workers to perform their duties safely and efficiently, often in the presence of fast-moving machinery, and to inspect in order to guard against accidents from falls. The illumination must permit the detection of breaks in the strata which presage falls, which are the most prolific source of accidents in mines.

During recent years there has been a considerable reduction in the number of accidents due to falls of the roof and sides. Usually the credit for this is given to investigations made into the principles underlying ground movements, roof control and support, but improved lighting has enabled the deputy and the officials to make much better inspections.

It is gratifying to find that nystagmus is being eradicated. In 1922 there were over 4 000 new cases, but by 1947—the last year for which official figures appear to have been published—there were only 842, and there is evidence that the improvement has been maintained.

It is difficult to highlight any marked effect of improved lighting on production in Great Britain. This has always surprised me, because in other industries it has invariably been found that the provision of improved lighting has led to increased production, and the same thing applies in the mining industry on the Continent. In Germany claims were made many years ago for considerable increase in output following the introduction of mains lighting at the coal-face, and similar reports have come from the French coalfields. In this country, however, we have never been able to show any real advantage in that direction. To my mind, the failure to produce increased output which might reasonably have been expected has been due to certain circumstances which are likely, under the present regime, to disappear, and I feel confident that beneficial effects will accrue in the future. Only a very slight increase in output per man-shift is necessary to balance the cost of suitable illumination.

Fig. 2 gives voltage discharge curves for lead-acid and alkaline batteries. What is the effect of the voltage drop on the light emitted by the lamps during, say, an 8-hour shift, i.e. the diversity factor, or the ratio of the maximum to the minimum light over a shift?

The low incidence of ignitions of firedamp from cap lamps indicates that the danger of such occurrences is somewhat remote, but will the author say whether the cap lamp is, or can be made, intrinsically safe?

Reference is made to the effect of adverse natural conditions, including thin seams and geological conditions. What is the minimum seam thickness for the use of mains lighting, and has the inclination of the seam any marked effect?

I agree that the mounting of lighting fittings on the snaking conveyor is a step in the right direction, as it solves the problem of moving up the lights at the face, which has hitherto been one of the main objections to mains lighting. This feature, combined with the prop-free front which is being increasingly adopted nowadays, should go far to solve the problem of mains lighting at the face, provided that the problem of glare can be dealt with.

With regard to the use of lighting systems for signalling, would the author say whether there is any maximum permissible period of blackout? Are any steps taken to ensure that this maximum period is not exceeded?

Mains lighting at the face will never eliminate the need to carry individual lights. I think local lighting will be necessary even where there is general lighting which eliminates the pervading gloom.

Mr. H. E. Collins: In the Durham Division during 1948–54 the proportion of cap lamps increased from 50 to 97%. During this period the number of fatal accidents fell from 65 to 4[illegible], non-fatal serious accidents from 330 to 195 and the number of certified cases of nystagmus from 82 to 29.

With regard to coal-face lighting, the impossibility of monetary assessment of advantages has retarded progress. Instinctively we all feel that adequate coal-face lighting results in more efficient and safer working. Instead of looking for financial advantages we should consider mains lighting at the coal-face as a means

improving working conditions. Formerly, a disadvantage of this system was the labour involved in moving forward the fittings at the completion of each cycle of operations. To-day, the lighting fittings can form an integral part of an armoured conveyor which is moved forward by means of hydraulic or pneumatic jacks. Although the ban on the use of aluminium has retarded progress, casings for the lighting units are now being made of malleable iron, since weight is no longer a governing factor.

There are two tungsten-filament units and one fluorescent-tube unit installed in the Durham Division. With these installations signalling is incorporated with the lighting. This is an important contribution to safety, and the momentary dimming of the light in no way impedes vision, although it reduces the life of the lamps. In the fluorescent installation the tube life on the face is 2 100 hours, while tubes used in the roadways have a life of 5 800 hours. The cost of this installation is 2·1d. per ton, and the intensity of illumination on the face varies from 7·75 to 0·4 lm/ft^2.

I should like the author's views on the light colour for these installations.

In these days of full employment, monetary inducement alone will not maintain a stable labour force. The industry must be made more attractive and it appears that an important contribution to this is adequate lighting.

Dr. J. W. T. Walsh: How does the man in charge of the lamps at a mine know when to change a bulb? The life of the bulb is nominally 200 hours, which means that, at normal voltage, it would only last for about 20 shifts. However, the author's curves indicate quite clearly that the voltage falls during the discharge of the battery and the life of the lamp is, presumably, considerably increased. How does one judge when the lamp is nearing the end of its life and ought to be replaced? I imagine that it is a serious matter if a man takes a lamp down to the face and it happens to fail within the first hour or so of the shift.

Mr. A. G. Penny: In Section 4.3.5 the author discusses the desirability of twin filaments and auxiliary filaments, and states that it is sometimes desirable to have two bulbs and sometimes to have two filaments in one bulb. 'Alternatively', he says, 'the auxiliary filament may be included in the main bulb, but it is generally accepted that a second filament is advisable.' Does this mean that a second bulb is advisable, or that it is universally accepted that there must always be two filaments somewhere in the cap lamp?

To complete the picture in regard to costs of coal-face lighting, could the author give the figures for cap lighting?

Mr. H. C. Fox: Mr. Collins mentions the colour of the light, but apparently is merely considering the slight difference between tungsten-filament and fluorescent lighting. Many motorists allege that on black roads the visibility is much greater with sodium lighting. Would it not be worth investigating, if it has not already been done, whether sodium lighting has any advantages for roadway lighting?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Dr. C. D. J. Statham (*in reply*): I consider that the present method of assessing the light-distribution ratio for cap-lamp reflectors cannot be materially improved, since it takes account of all the variables involved and the measurement is not difficult. The procedure suggested by Mr. Metcalf would not take account of the output efficiency of the cap lamp, which varies with different types of reflector and with different designs of lamp. From the users' point of view the ratio is of real significance only when it expresses the relationship between the light in the central part of the beam and that over the whole field illuminated by the lamp.

The advantages outlined in Section 4.3.10 also apply in part to alkaline self-help systems, but to a lesser degree than to lead-acid self-service ones. Exposing the contacts of a cap-lamp alkaline battery for examination each day when the lamp is put on charge is of questionable advantage, and to my mind is offset to some degree by the liability of disturbing good contacts and the increased possibility of producing bad ones.

Cap-lamp developments in the near future will probably be concerned with improvements in battery capacity for similar weight and bulk and the betterment of headpiece lighting efficiencies; I feel sure that, at the same time, the problems of glare and voltage maintenance will be given attention by the designers.

Mr. Metcalf's comments on the difficulties associated with the use of aluminium alloys underground are timely and valuable, because these difficulties are impeding progress, although Mr. Collins's mention of heavier units being acceptable when mounted on the conveyor structure offers a solution where such arrangements are feasible.

On the question of signalling with mains-fed lighting installations, it is obvious that there is some difference of opinion upon the merits of such systems. In reply to Prof. Statham, no attempt is made to limit the period of darkness when signalling, and in practice no difficulty has been found to arise from this cause.

Although Dr. Roberts's remarks on the light distribution of cap lamps are theoretically true, I consider that, in practice, the user does not notice any material restriction in the field of vision and the object observed is usually adequately illuminated.

Development work on semi-portable lamps for use underground has been in progress for some time and a design is at present under consideration. It is considered, however, that these units do not provide a completely satisfactory substitute for mains lighting. Such units, however, would be useful in circumstances where mains-lighting systems would not be convenient or practicable.

Prof. Statham's comments on the effect of lighting upon safety and health emphasize the importance of lighting below ground, and it is indeed unfortunate that it is not possible to attribute to lighting its true share of the credit for the greatly improved conditions in mines in recent years. It is becoming increasingly apparent that the use of mechanized methods of production demands improved lighting standards for their success.

The diminution in the mean spherical candle power of a cap lamp over an 8-hour shift is about 18–20% with lead-acid batteries and about 30% with nickel–cadmium batteries.

Present-day cap-lamps are extremely safe, but it is not possible to claim that they are intrinsically safe owing to the hot filament of the bulb, which would cause an ignition in certain circumstances if exposed in an inflammable atmosphere. However, there are a number of devices used in cap lamps which minimize this hazard, and further developments are in progress.

Owing to the congestion of roof supports and machinery on the coal-face, it is obvious that it will not be advantageous to employ mains-lighting systems in very thin seams; in my opinion the minimum thickness is of the order of 3 ft. The inclination of the seam is of little consequence, except as regards the effect it may have on the supporting and handling of the equipment.

Mr. Collins's statistics and practical comments on actual installations of mains lighting are valuable and again emphasize the vital importance of lighting underground.

On the subject of colour, we should aim at something as near

as possible to natural daylight in order to produce ideal conditions analogous to those pertaining on the surface. Monochromatic light sources should be used only after careful consideration, for the lack of definition in certain circumstances may be a serious disadvantage.

In reply to Dr. Walsh's question concerning the changing of bulbs in miners' lamps, the actual life of a bulb is 500–600 hours, which represents about 3 months' working. Photometric readings are generally taken of each lamp every 4–6 weeks, and bulbs are replaced when they show a low light output. Naturally, some bulbs burn out below ground, but this contingency is generally met by the pilot bulb or second filament in the main bulb.

In some makes of cap lamp, both main and auxiliary filaments are included in one bulb and may be of the same or different current ratings, whereas other lamps have the second filament in a separate pilot bulb. In Britain it is becoming generally accepted that there should be two filaments somewhere in the headpiece.

The cost of cap-lamp lighting varies considerably from one colliery to another, according to the size and efficiency of the undertaking. An average figure would be of the order of 2d.–2½d. per ton of coal won.

In reply to Mr. Fox's question, sodium-vapour fittings would not be permitted underground in coal mines, owing to the inherent danger of ignition of inflammable atmospheres.

DISCUSSION ON 'THE USE OF ELECTRICITY IN THE PRODUCTION OF CALCIUM CARBIDE'*

WESTERN UTILIZATION GROUP, AT CARDIFF, 28TH NOVEMBER, 1955

Mr. C. H. H. Pease: I am interested in the method of towering the electrode, which seemed cumbersome. Could the author state whether consideration has been given to automatic control?

What was the rate of consumption or travel of the electrode, and was there any means of indicating when it was time for its next 'slip'?

Mr. A. N. D. Kerr: As the power factor of this installation is to be improved by the use of fixed capacitors, and their capacitance in relation to the total load is substantial, has any consideration beeen given to the effect this may have on the increase in apparent power now likely on short-circuit?

I note that the motors in this process are of the squirrel-cage pattern and are started by direct switching. I should like to make a plea for greater support for this method from the supply industry. By contrast with the star-delta method it avoids the peak currents on switching over from start to run, as there is only one initial surge.

Has the author any totally-enclosed and air-cooled squirrel-cage motors, built to British Standard dimensions, in commission? Is the formation of condensate a problem, and if so, how is it tackled?

Mr. T. E. Reece: I note that the author refers to a reduction of furnace load on request by the supply authority if it is economically feasible. What is this economic limit and at what percentage load does this occur, and is the quality of the carbide involved?

The furnace transformers described in the paper are equipped with off-load tap-changing gear. I think that future developments should incorporate on-load features, which would result in greater flexibility.

What developments are taking place to effect a reduction in heat losses due to escaping gases in the main furnace and the losses amounting to some 10% in the electrode preparation furnace due to contact of hot calcined anthracite with air? Perhaps the use of an inert-gas shield at this point would be feasible.

Mr. G. H. Bowden: Reference has been made to the use of capacitors for power-factor correction of the main furnace loads. It is understood that the arc current is not sinusoidal. Does this result in the generation of any substantial harmonic content?

Extremely heavy currents are involved, and these are conveyed to the furnace by means of interleaved busbars. Is overload protection on the primary side of the transformers effective in preventing serious damage following the failure of low-voltage insulation?

Mr. C. J. Beavis (*in reply*): In reply to Mr. Pease, there are automatic electrode control systems in use and, in fact, our latest furnace is so equipped with a system which uses electrode current as the control element. Another system uses furnace power as the control. Electrode consumption varies in proportion to the carbide produced, and in our furnaces it is approximately 1¼ in per hour. Assuming the furnace to be working at its normal output, the rate of electrode 'slipping' is calculated on a time basis using the above figure of consumption.

With regard to Mr. Kerr's question on power-factor improvement, the possible effect of capacitors in relation to the short-circuit kVA has been considered. It has been shown that, if these are installed on the 11 kV side of the auxiliary transformers, the existing switchgear will be satisfactory. I regret that I am unable to give any information regarding the formation of condensate in totally-enclosed fan-cooled motors to British Standard dimensions, as there are only one or two in service at the factory.

In reply to Mr. Reece, a 30% load reduction is regarded as being the economic limit for the furnaces. Beyond this point quality is adversely affected. With regard to his comment on furnace transformers, I would agree that on-load tap-changing gear would be an advantage under some conditions in furnace operations. The heat lost in the carbide furnace stacks owing to the burning of carbon monoxide to carbon dioxide could be recovered by building what is known as a 'closed' furnace. In this, the admission of air above the hearth is prevented by using a fully closed hood and the recovered carbon monoxide is then cleaned and can be used in other parts of the factory, say for lime production and/or coke drying.

It is not considered economically worth while to recover the gases lost in the anthracite calcining furnaces. Incidentally, the figure mentioned by Mr. Reece is probably somewhat high.

Mr. Bowden mentions the possibility of the generation of harmonic currents owing to the use of capacitors for power-factor correction. This has been considered, and, in fact, tests have been carried out. It was shown that, under all furnace operating conditions, the effect of any harmonics generated would be negligible. Overload protection on the primary side of the furnace transformers appears to work reasonably satisfactorily and extensive damage to the busbars following a flashover has so far not been serious, although it certainly does result in the loss of some copper each time it occurs.

* BEAVIS, C. J.: Paper No. 1721 U, October, 1954 (see 102 A, p. 217).

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Paper No. 1998 U
Jan. 1956

THE POTENTIALITIES OF RAILWAY ELECTRIFICATION AT THE STANDARD FREQUENCY

By E. L. E. WHEATCROFT, M.A., M.I.Mech.E., and H. H. C. BARTON, B.A., M.I.Mech.E., Members.

(*The paper was first received* 2nd *September, and in revised form* 21*st November*, 1955. *It was published in January*, 1956, *and was read before* THE INSTITUTION 2*nd February*, *the* NORTH-EASTERN CENTRE 13*th February*, *the* NORTH-WESTERN UTILIZATION GROUP 19*th March*, *and the* RUGBY SUB-CENTRE 20*th March*, 1956.)

SUMMARY

The paper discusses the technical and economic aspects of railway electrification using alternating current at the standard frequency. The authors accept that, for suburban traffic, d.c. electrification has provided a satisfactory operating, technical and economic answer, and they put forward the view that for new mainline projects the 50 c/s system is likely to be cheaper than other systems and may be installed without technical difficulty.

(1) INTRODUCTION

Until the end of the Second World War the so-called "battle of the systems" lay between the direct-current system, in which current at voltages of up to about 3 kV was supplied to trains powered with series-wound traction motors, and the low-frequency a.c. system whereby single-phase current at 11–16 kV was supplied to the trains and thence by transformer, in most cases direct to a.c. commutator motors. Motor-design difficulties necessitated the adoption of a frequency lower than standard, i.e. $16\frac{2}{3}$ or 25 c/s, requiring current to be supplied to the line either by special alternators located at the traction substations and driven by 3-phase motors from the standard frequency supply or, as in Germany, Switzerland and parts of the United States, from special low-frequency generating stations.

The series-wound d.c. motor has proved particularly suitable for traction, but because of motor-commutation voltage limitations, the d.c. system suffers the disadvantage of having to operate at a comparatively low line voltage and with high currents. This necessitates more costly fixed equipment because of the relatively large conductor section and the greater number of substations which are required.

With the a.c. system, incorporating transformers on the rolling stock, much higher line voltages were possible, resulting in lower line currents. This permitted lighter and cheaper track equipment and fewer substations, and reduced the cost of fixed equipment even after allowing for the conversion equipment to supply the low-frequency current. It was always obvious that the cost of fixed equipment could be reduced still further if technical advances would allow the trains to be supplied with alternating current at standard frequency, as the substations would then be merely transforming stations, while the high line voltage would permit light track equipment and well-spaced substations as in the low-frequency case.

(2) HISTORICAL

Roughly two-thirds of the world's electric-railway route mileage is d.c. operated, and one-third is a.c. operated, comprising a varied assortment of voltages and frequencies. In Europe there are some 9 000 route-miles equipped at $16\frac{2}{3}$ c/s, this being the system adopted by the national railways of Austria, Germany, Sweden and Switzerland. In all these countries the low-frequency a.c. system proved successful on technical grounds, and extensions of electrification were therefore justifiably carried out using the same system.

In the United States trends differed. The electrification of sections of the Chicago, Milwaukee, St. Paul and Pacific Railroad at 3 kV d.c. in 1915, before the static rectifier had been developed for traction, conflicted with the decisions of some other lines to adopt 11 kV 25 c/s. However, at that time 60 c/s had not been established as a national standard and 25 c/s industrial frequency networks existed; there were in fact two standards. Perhaps, therefore, America may be credited with being the first country to adopt a standard frequency for railway electrification, because the $16\frac{2}{3}$ c/s system, which had already proved successful in Europe, was rejected in favour of an existing industrial standard.

In the 1920's, in the British spheres of interest in South America, South Africa, Australia and India, a large mileage was equipped for d.c. operation with rotary-convertor substations. By the late 1930's static rectifiers were well established for traction applications (they had been used on the Midi Railway since 1922), and the Italian Railways decided to adopt the 3 kV d.c. system. At this time only a very limited experience had been obtained with 50 c/s for traction, the alternatives being the d.c. system with its excellent motor characteristic and now cheapened and improved technically by the rectifier, and the low-frequency a.c. system which still offered lower fixed equipment costs on account of its higher operating voltage. This Italian decision, which was supported by similar decisions in Eastern Europe, Belgium and Holland, as well as by the Lackawanna Railroad in the United States, is significant because it involved a new major project (the 3-phase system in the Italian northern provinces was time expired), and it was taken when extensive experience had been obtained with each alternative.

In France extensions of electrification were put in hand after the Second World War by the Société Nationale des Chemins de Fer Français under whose direction the railways were by then fully nationalized. Prior to this, several years' satisfactory experience had been obtained with a 50 c/s system in Hungary, equipped in 1932 between Budapest and Komárom and later extended to Hegyeshalom. The German State Railways had tried different types of rolling stock on the experimental 50 c/s Hollental line, which had been operating 35 electrified route-miles since 1936. In order to consolidate and extend this experience the French Railways opened a short experimental 50 c/s section in Savoy in 1950. This was considered so successful that the standard-frequency system has been adopted for the major electrification projects in N.E. France, the first section of which was opened to traffic between Valenciennes and Charleville in 1954. This decision is the more significant because, apart from the large mileage involved, it was taken in spite of the fact that some 2000 route-miles of successful 1·5 kV d.c. railway electrification already existed in the French central and south-western provinces.

While these developments were proceeding the Chemin de Fer

This is an "integrating" paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Wheatcroft and Mr. Barton are with Merz and McLellan.

Table 1

RAILWAY ELECTRIFICATIONS AT THE STANDARD FREQUENCY WHICH HAVE BEEN COMPLETED OR PROPOSED (POSITION AT 1955)

Railway	Route	Route miles	Track miles	Line voltage	Rolling stock	Completion date
		miles	miles	kV		
Hungarian State	Budapest–Komárom	56	404	16	36 locomotives	1932
Hungarian State	Komárom–Hegyeshalom	61			4 railcars	1934
Hungarian State	Budapest Extensions	23	77		†	1954
D.B. (Hollental)	Freiburg–Seebrugg–Neustadt	35	57	20	5 locomotives 1 motor-coach	1936
S.N.C.F. (Savoy)	Aix-les-Bains–La Roche-sur-Foron	48	50	23	4 locomotives 4 motor-coaches	1950–51
B.R.	Lancaster–Morecambe	10	19	6·6*	3 motor-coaches	1953
B.C.K. (Congo)	Jadotville–Tenke	64	130	25	12 locomotives	1951
B.C.K. (Congo)	Tenke–Kolwezi	62				1953
B.C.K. (Congo)	Jadotville–Elisabethville	84	100		10 locomotives	Uncompleted
S.N.C.F.	Valenciennes–Charleville	89	256		105 locomotives	1954
S.N.C.F.	Charleville–Thionville	90	294			
S.N.C.F.	Thionville–Reding–Basle	193	710	25	85 locomotives	Uncompleted
S.N.C.F.	Valenciennes–Lille	35	109			Uncompleted
S.N.C.F.	Dole–Vallorbe, Frasne–Portarlier	73	111		105 locomotives	Uncompleted
S.N.C.F.	Nord–Paris	350	951			P (1958–59)
S.N.C.F.	Nord–Est	410	†	25	150 locomotives	P
U.S.S.R. State	Lichoslaul (Kalinen–Boogoje)	38	†	22	† locomotives	1951–52
U.S.S.R. State	Ozherelye–Pavelets	62	†	22	† locomotives	1955
Turkish State	Istanbul Suburban	17	46	25	36 motor-coaches 3 locomotives	1955
Portuguese State	Lisbon–Entrocamento (1st stage)	92	180	25	15 locomotives	Uncompleted
Portuguese State	Entrocamento–Oporto (2nd stage)	150	284		25 3-car units	Uncompleted
Argentine and Chile	Mendoza–Los Andes	125	†	27	11 locomotives	P

* Provisional voltage because some original 6·6 kV line equipment is being used for this experimental section.
† Some oversea details have yet to be obtained.
P Proposed.

Table 2

PARTICULARS OF 50 c/s SERIES-WOUND COMMUTATOR TRACTION MOTORS BUILT OR PROPOSED (POSITION AT 1955)

Type No.	Design	No. of poles	One-hour rating: Voltage	Current	Speed	Weight	Manufacturers	No. of motors ordered or proposed	Where operating or proposed for operation
			volts	amp	m.p.h.	lb			
TDM.627	Twin	2 × 12	2/218	1 600	61	11 100	Alsthom	7	In service on loco CC 20002 Savoy section, S.N.C.F.
16WB880	S.A.	16	250	2 780	40	6 520	Oerlikon	51	In service on loco CC 20001 Savoy section, S.N.C.F. 44 motors are ordered for locos 25001–7 for Savoy extensions, S.N.C.F.
20WB1140	S.A.	20	283	3 760	53	8 800	Oerlikon	10	For locos BB.30001–2 for extensions to Basle, S.N.C.F.
14HW750	S.A.	14	251	1 670	36	3 750	Oerlikon	5	In service on motor-coach Z9051 Savoy section, S.N.C.F.
MS92	S.A.	18	260	3 000	33	9 600	Jeumont	218	36 motors on BB class 13 000 locos in N.E. France; a further 182 proposed for extensions
MS93	S.A.	18	365	2 900	58	9 800	Jeumont	—	Prototype motor proposed for subsequent S.N.C.F. electrifications
EKB750	Tandem	2 × 12	2/235	1 490	46	7 480	A.E.G.	4	In service on loco E.244.22 Hollental section: DB
WBM196	Twin	2 × 14	2/243	1 370	47	5 500	Siemens	8	In service on loco E.244.21 Hollental section: DB
WBM244	S.A.	12	220	1 970	38	5 610	Siemens	4	In service on motor-coaches ET.255 Hollental section: DB
MS51	Twin	2 × 10	2/240	850	29	5 925	A.C.E.C.	48	In service on the 12 locomotives of the B.C.K. Railway, Belgian Congo
MN93	S.A.	18	235	2 420	30	7 700	A.C.E.C.	40	For a further 10 locos of the B.C.K. Railway
KJ107	S.A.	14	242	3 150	*	7 250	A.S.E.A.	—	Prototype motor under test
TAM639	S.A.	12	260	1 400	39	4 840	Alsthom	72	Istanbul Suburban (motor-coaches)
MS72	S.A.	14	300	1 880	37	6 380	Jeumont	12	Istanbul Suburban (locomotives)
OSA750	S.A.	12	230	1 200	39	3 520	Oerlikon	100	Lisbon Suburban (motor-coaches)

Notes.—S.A. Single armature.
* Rating at 70% full speed.

du Bas-Congo au Katanga embarked upon a major 50-c/s project in the Belgian Congo. First opened in 1952 between Jadotville and Tenke, this has now been extended to Kolwezi, and a further section is under construction to Elisabethville. In Great Britain and Russia trials have also been made with this system, the Lancaster, Morecambe and Heysham section of British Railways having been in successful revenue service for over two years after conversion to 50 c/s operation.

Table 1 summarizes the published particulars of all the standard-frequency systems which have been completed or proposed to date, including recent projects in Turkey and Portugal.

(3) TECHNICAL CONSIDERATIONS

(3.1) Rolling Stock for 50 c/s Operation

Three basically different types of rolling stock are available for standard-frequency electrifications, all of which may be seen in operation. They are the a.c.-motored type, the motor-generator type with d.c. motors or a.c. induction motors, and the rectifier type with d.c. motors. The technical details of these types are fully described in the References given in Section 6, and discussion is therefore confined to the assessment of the performance of these types so far as experience permits. This experience under different service conditions is limited, and there has hardly yet been time for the maintenance departments to contribute worthwhile opinions.

(3.1.1) 50 c/s Motored Rolling Stock.

To date, about fourteen different designs of 50 c/s commutator traction motors have been built, and details of these are given in Table 2. Some of these have not yet entered service, while others are acknowledged prototypes.

Single-phase traction-motor design is fundamentally difficult because of the "transformer e.m.f." which is induced between field and armature, resulting in the armature windings having to carry excessive currents when starting which are not torque-producing. This necessitates a design compromise between the provision of a large commutation area and operation at a comparatively weak flux per pole with a consequential increase in the number of poles (and therefore brushes) in order to obtain adequate starting torque. This difficulty, significant at low frequencies, increases appreciably as the frequency is raised, until at 50 c/s the incorporation of additional design techniques or combinations of these techniques becomes essential. These include tandem or twin construction, field shunting on the early starting notches in order further to reduce the flux, the incorporation of resistive elements within the armature windings to reduce the non-torque-producing currents, and resistive shunting of interpoles to improve commutation. These features tend to complicate motors and equipment to the disadvantage of maintenance as well as increasing motor size and weight. Fig. 1 illustrates the effect of an increase in frequency on motor size and weight, the two motors being up-to-date $16\frac{2}{3}$ c/s and 50 c/s machines designed for similar duties by the same manufacturer.

So far as it is possible to judge, the $16\frac{2}{3}$ c/s traction motors in service on the Continent have a better maintenance record than the 25 c/s motors in service in America. Nothing the authors have seen of 50 c/s traction-motor maintenance work suggests an easing of this trend; indeed they are of the opinion that the opposite may be the case as more operating experience is obtained with 50 c/s machines.

For multiple-unit applications, where forced starts and rapid accelerations are an essential requirement, the 50 c/s traction motor has a better chance provided that it can be accommodated within the limited space usually available and within the axle loads permitted. The total weight of 50 c/s and $16\frac{2}{3}$ c/s equip-

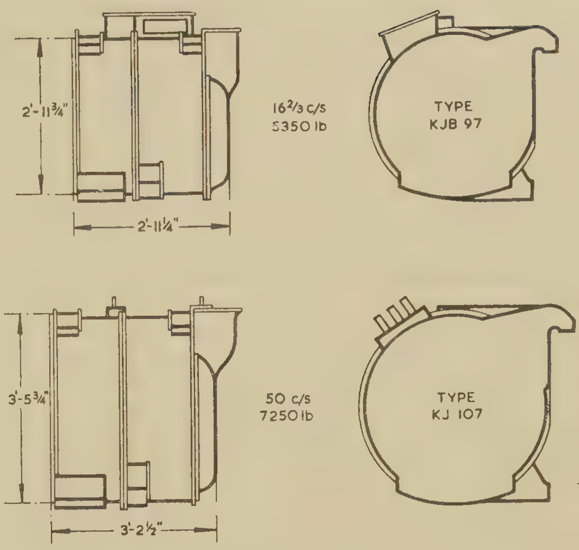

Fig. 1.—Sizes and weights of $16\frac{2}{3}$ c/s and 50 c/s traction motors designed for similar duties.

ments for multiple units as well as locomotives would be about the same, the heavier 50 c/s motors being offset by the lighter 50 c/s transformer. The objections to 50 c/s traction motors therefore lie in the maintenance problem which they are likely to present, coupled with an unavoidable increase in unsprung weight if they are axle-mounted.

(3.1.2) Motor-Generator Rolling Stock.

Motor-generator locomotives may be designed either with d.c. generators and d.c. traction motors or with single-phase/3-phase motor-alternator sets and 3-phase induction motors. In the former case, speed control is obtained by varying the d.c.-generator output, while in the latter case this is done by varying the frequency at the traction motors. Both types have a poor power/weight ratio, which renders them less economical for mixed traffic duties. They may, however, be designed for a unity or leading power factor, with the result that they help to boost the line voltage when operating in conjunction with other types.

The d.c.-motored type has excellent starting and slow-running characteristics, and it is best suited to conditions which permit heavy freight trains to be worked entirely by a locomotive "link" comprising this type. This is evidenced by their remarkable performance operating the coal traffic on the Virginian Railway. The control equipment for varying the generator field strength is comparatively simple, and the regenerative brake feature may be incorporated easily.

The frequency-changer type is technically more versatile because better performance may be maintained into the higher speed ranges. There are two main versions of this type. Earlier versions used in Hungary have wound-rotor induction motors with slip rings fed at a number of fixed frequencies, intermediate speeds being obtained by resistance control. In one case four fixed speeds are obtained by traction-motor pole-changing, while in another a frequency-changer is coupled to a phase convertor and runs at synchronous speed, five fixed frequencies being obtained by pole-changing and varying the direction of rotation of the frequency-changer field. A later version recently ordered by the French Railways has squirrel-cage traction motors in which the phase convertor and frequency-changer are each coupled to a separate d.c. machine for Ward Leonard control. The phase convertor rotates at synchronous speed, but the frequency-changer, having variable speed control, enables a

continuous frequency variation between 0 and 135 c/s to be applied to the traction motors. This latest version possesses most of the advantages of the a.c./d.c. type with perhaps an added one, because the squirrel-cage induction motors should require less maintenance than even d.c. machines.

The main objections to the frequency-changer type of locomotive seem to lie in its complication and the low power/weight ratio. The latter objection becomes more significant when the locomotive is used for the wider range of duties for which its performance is suitable. These disadvantages will generally preclude the use of motor-generator transformation for multiple-unit applications.

(3.1.3) **Rectifier Rolling Stock.**

Many factors point to rectifier-equipped rolling stock with d.c. traction motors providing the best all-round answer—an opinion the authors have held for some time. Following very successful trials on the Pennsylvania Railroad with a rectifier motor-coach in 1949 and, more recently, with two large rectifier locomotives, 10 locomotives and 100 multiple-unit coaches of this type have been built for operation on the New York, New Haven and Hartford Railroad, and six 2-unit 6000 h.p. rectifier locomotives have been ordered by the Virginian Railway. These are significant moves to make on 25 c/s systems, where the problems of a.c. traction-motor design are less exacting than is the case on 50 c/s systems. Furthermore, on the French Railways, where more experience of different types of standard-frequency rolling stock has been obtained to date than elsewhere, rectifier locomotives are being ordered in increasing numbers, following the good results obtained with those already in service in N.E. France. Altogether there are now about 170 rectifier locomotives and 105 rectifier motor-coaches in service and on order for different railways.

Rectifier rolling stock enables the well-proven d.c. traction motor to be adopted; indeed, in America, existing standard d.c. motors have been used. This type also offers scope for relatively simple and efficient dual-system operation, which may be advantageous if main-line electrification projects embrace an existing d.c. system over part of the route. This consideration weighed with the New York, New Haven and Hartford Railroad in their decision to adopt rectifier designs both for locomotives and multiple-unit stock for inter-running with the New York Central d.c. system, although it is understood that the primary justification lay in the wish to adopt the more easily maintained d.c. traction motor.

So far, except for a few multi-anode experimental equipments, most of the service experience with rectifier rolling stock has been obtained with the single-anode ignitron rectifier. British Railways have, however, successfully used air-cooled "excitrons" on one of the Lancaster, Morecambe and Heysham motor-coaches, and the French Railways are also carrying out experiments with this rectifier, which may offer some reduction in complication by the simplification of the "firing" equipment. Nevertheless, it may be said that the ignitron rectifier, although requiring firing as well as water-cooling equipment, which were expected to be disadvantages during the early application stages, has now established itself as an easily accommodated and acceptable proposition for railway applications.

Already the French Railways claim that a comparable 50 c/s ignitron locomotive is capable of a better performance than its all-direct-current counterpart. This results from the transformer-tap method of control, whereby a large number of starting notches may be incorporated easily, and from the improved adhesion which is obtained with parallel-connected traction motors. While this improved adhesion is a feature of all rolling stock having parallel-connected traction motors, irrespective of whether they are a.c. or d.c. operated, it can be used to better advantage with d.c. motors having high saturation. On straight d.c. locomotives the adhesion qualities cannot be so good because the traction motors are series-connected during starts. This results in a tendency for slipping to be cumulative owing to a voltage build-up across the motor of the slipping wheel, combined with the falling off of tractive effort at those wheels which are gripping.

In the field of rectifier alternatives it must not be overlooked that rapid progress is being made with the development of semiconductor rectifiers for heavy and fluctuating current duties. It is certain that their application to traction is not far distant, with a consequent simplification of equipment both in design and layout and an appreciable saving in space and possibly weight. Their rigid construction seems well suited to traction applications.

The authors consider that the trend in favour of rectifier equipments is likely to continue, because they may be designed to be comparable in performance with straight d.c. equipment without occasioning any increase in maintenance. Given reasonably large orders, rectifier locomotives should be no more costly than 3 kV d.c. types. The purchase of rectifier rolling stock for three 25 c/s American railways, as mentioned above, is an important pointer.

(3.2) Dual-System Operation

Rolling stock may be designed for inter-running between a high-voltage a.c. traction system and a lower-voltage d.c. one. Designs having d.c. traction motors supplied from rectifiers are very suitable for this because the rectified voltage may be selected, as in the case of the New Haven Railroad, to enable the traction-motor circuits to be fed direct when in d.c. territory. Dual-system rolling stock of this type requires resistance control for operation from the d.c. system, and it may therefore be more economical to use this resistance control instead of transformer-tap control when on a.c. territory, thus avoiding duplication of equipment.

Where dual-system operation between a high-voltage a.c. system fed from overhead conductors and a low-voltage d.c. system fed from current rails is required, the track equipment may overlap. This permits automatic change-over from pantograph to shoegear and vice versa, with only a short coasting period while the transition switchgear operates. Inter-running in this way offers an alternative deserving of economic consideration if clearances for the entry of an overhead-line high-voltage system into or through large cities prove excessively costly to obtain.

Dual-system operation between a high-voltage a.c. system and a d.c. one having overhead conductors presents additional problems, not the least of which is that of pantograph design. The switching arrangements may be similar to those used in the former case, but higher-voltage traction motors would have to be installed than would be necessary if rectifier locomotive operation were limited to a.c. territory.

Dual-system operation between a standard-frequency a.c. system and a suburban d.c. system is easier than it would be between, say, a 3 kV d.c. system and a lower-voltage suburban one. The latter would require the installation of complicated switchgear in each locomotive, and the traction motors would have to be insulated for the higher voltage and wound for the lower one. Perhaps the worst feature of d.c.-to-d.c. dual-voltage designs is that the traction motors must remain series-connected while operating from the higher-voltage system, where it is likely that a greater running time will be spent.

These considerations of inter-running are based on the assumption that rolling stock should be capable of the most efficient

operation on both systems without involving drivers in extra duties such as changing motor combinations or controller notches in order to obtain the desired performance when running from one system to another. The manual monitoring of automatic change-over equipment has already proved acceptable.

(3.3) Substation Spacing

A major factor affecting substation spacing is the drop in voltage which can be tolerated at the trains. Expressed as a percentage of the nominal voltage, this may be taken to be not more than about 20% under normal conditions and 50% for limited periods under abnormal conditions. The latter applies to the failure, assumed quite rare, of substation equipment or part of the supply system; the voltage drop must then be limited to a value which will keep trains moving without shutting down essential auxiliaries such as brake exhausters or compressors. On d.c. main-line systems, where single-unit rectifier substations are in use, it will be desirable to work near these limits in order to keep the fixed costs for substations and track equipment to a minimum. Since the voltage drop is resistive it is inversely proportional to the cross-sectional area of the conductors and directly proportional to the distance between substations.

With an a.c. system the voltage drop is due mainly to the reactance, which is largely independent of conductor cross-section but directly proportional to frequency. It follows, therefore, that the cross-sectional area of the conductors may be reduced to the minimum size required for mechanical reasons with much less effect on either voltage drop or substation spacing than would be the case with d.c. systems.

Continental experience with $16\frac{2}{3}$ c/s a.c. electrifications on lines of varied traffic density has shown that a nominal voltage of 15 kV leads to such a wide substation spacing on purely technical grounds that practical considerations, such as the convenience of supply points and route topography, take charge rather than the consideration of voltage drop. The widespread use of this voltage for many years suggests that it is a good compromise.

If similar substation spacing is adopted for a standard-frequency system the effect of the trebled reactance must be taken into account. This can only be done by raising the voltage and not by increasing the copper cross-section. The equivalent voltage at 50 c/s is about 25 kV.* Under some conditions substation spacing may be governed by current density in the conductors. This will, however, be exceptional rather than the rule and does not affect the basic argument.

* Since $\left(\frac{15}{25}\right)^2 \simeq \frac{16\frac{2}{3}}{50}$

(3.4) Power Supply and Connections

With a low-frequency a.c. system the substations which, as mentioned previously, are few in number, comprise 3-phase/1-phase motor-generator sets, and the line conductors are supplied at one phase throughout the whole system. They may therefore be continuous with sectioning points for maintenance purposes only. In this case, the current taken from the 3-phase supply system is balanced between the phases. With a 50 c/s system the substations comprise only static transformers, and there is an inherent difficulty in balancing the three phases of the current taken from the supply system. A method adopted in the French electrifications is to make each intermediate substation comprise a 3-phase/2-phase Scott-connected transformer, the line equipment being sectioned at the substation and one direction supplied by each of the two secondary windings. If the currents drawn in the two directions happen to be equal, the 3-phase current is then balanced. With sections carrying comparatively dense traffic the Scott connection may be used with advantage because in these cases both halves are likely to be well loaded and approximate balance will be obtained on the 3-phase side. On light-traffic sections, while the Scott connection is still an advantage, it may not be justified if the railway load is very small compared with the industrial load.

An alternative method is to sectionalize the overhead line equipment into 3, 6, or 9 "equal" parts (equal in terms of average loading), which can be supplied from the three phases. These are then balanced overall on those occasions when the loads are, in fact, equal. Fig. 2 shows such an arrangement for supplying three sections by "double-ended feed" from four substations. By this arrangement, security of supply is economically obtained with a spare single-phase transformer at each of the substations, with arrangements in the intermediate ones for these spare transformers to be connected to replace whichever phase transformer is out of service. It will be seen that the Scott connection has been replaced by the "open V" connection. The disadvantage of this method is, of course, that the supply to any one substation is never balanced. The effective overall balance may, however, be judged by the chart in Fig. 3. This is based on a light-traffic-density project study, and it shows the positive and negative phase-sequence components calculated from the $\frac{1}{2}$ min demands drawn by all the starting and running trains on the three sections over one hour, as deduced from the train diagram. It will be seen that the negative-phase-sequence component has a number of high peaks, but on the average it is only about 30% of the positive component.

Experience in France and the Belgian Congo of working

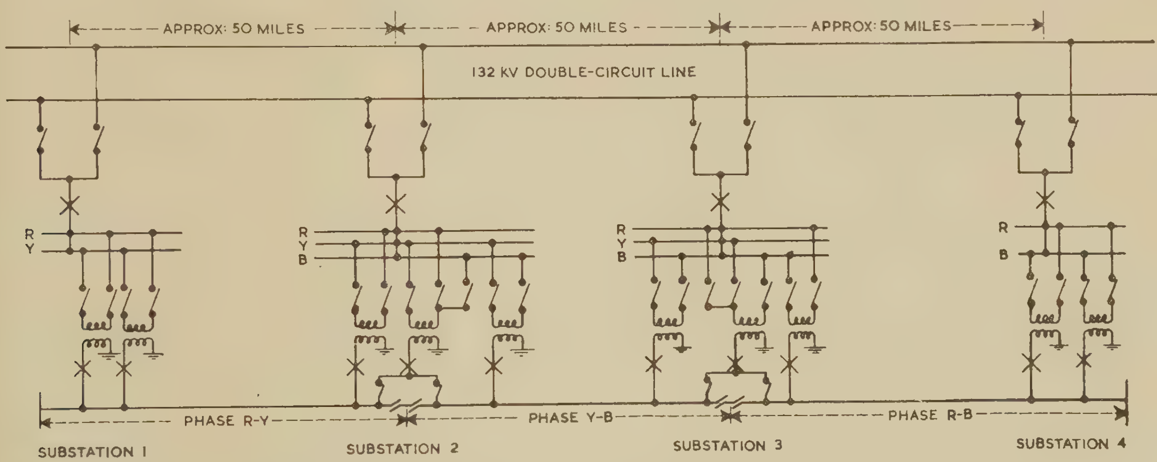

Fig. 2.—The "double-end feed" arrangement for supplying three sections of line from four substations.

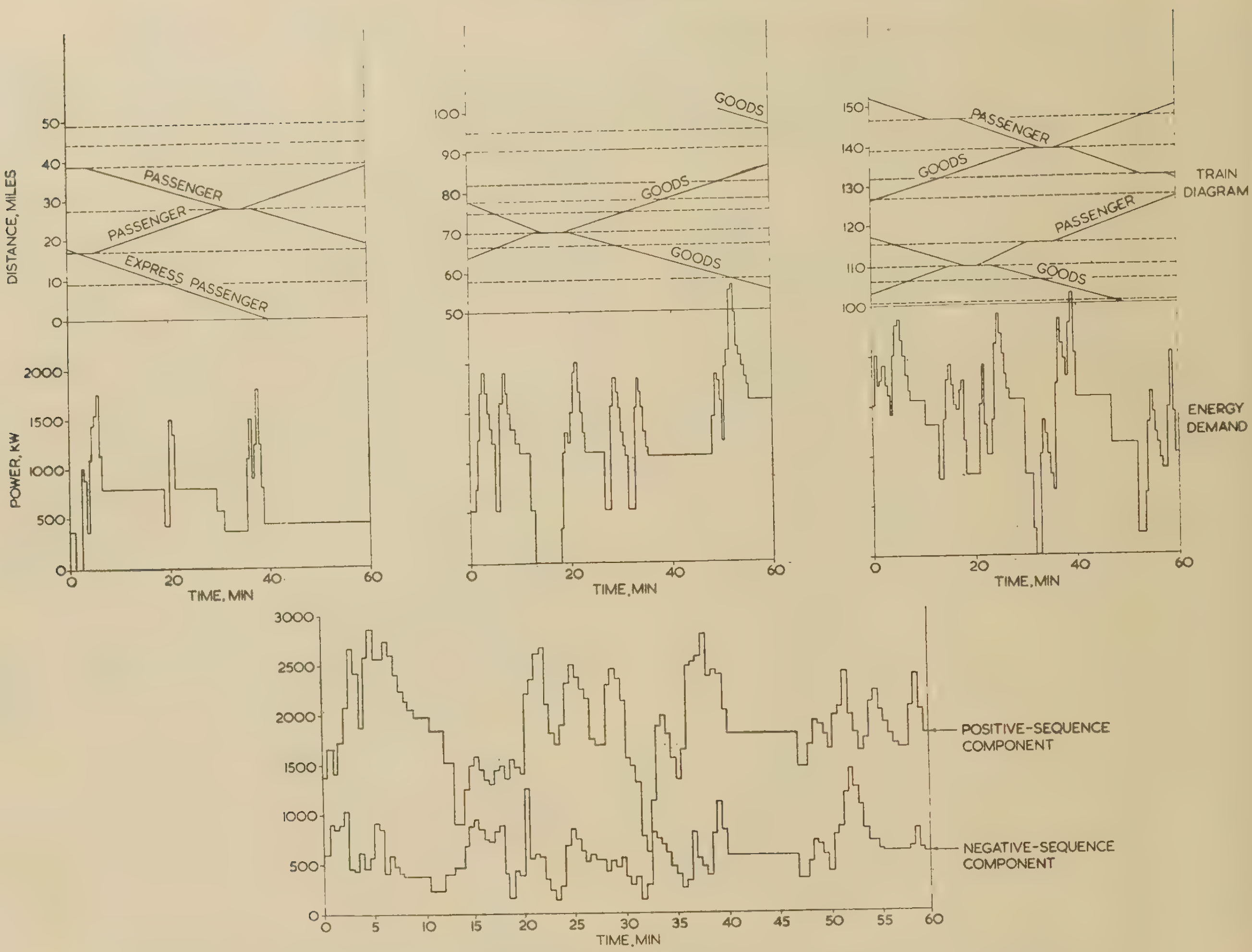

Fig. 3.—Energy demand of a standard-frequency electrification supplied from a 3-phase system.

trains through line equipment "dead sections" separating the phases has been satisfactory. Switches are provided to energize a "dead section" in an emergency, and these are suitably interlocked in order to ensure correct operation.

(3.5) Harmonics and Power Factor

The belief has already been expressed that the rectifier locomotive will prove the most suitable for a.c. electrifications. The waveform of the current drawn from the overhead line, and hence that from the supply, will therefore contain serious harmonics. This fact must be added to the other factors already mentioned (i.e. rapidly varying load and phase unbalance), which have to be met by the supply authority. The harmonics to be expected are of the following order:

3rd harmonic	20–28%
5th harmonic	10–15%
7th harmonic	5–9%
9th harmonic	·3–7%
11th harmonic	2–4%
13th harmonic	2–3%

The higher figures apply when there is heavy smoothing in the d.c. circuit. At one time it was thought necessary to incorporate heavy smoothing on the d.c. side in series with the traction motors, on the view that motor commutation would suffer from an undulating current. Chiefly as a result of American experience it is now considered that, at the most, 20–30% smoothing of the undulations is sufficient, and therefore the waveform distortion on the a.c. side may be somewhat ameliorated.

Because of the peaky nature of its demand, any traction load is tolerable to a supply system only if it is rather small compared with other loads, or what comes to the same thing, if it is supplied through feeders of low impedance. If the network is "strong" enough to supply the "peaky" loads which are inherent in traction (whether electrified on an a.c. or a d.c. system) it is generally strong enough to tolerate the phase unbalance and the harmonics. In most cases the railway load forms a small part of the total load and does not tend to expand at the same rate. Thus it is unlikely that the use of single-phase rectifiers on rolling stock will cause any additional embarrassment.

The power factor of rectifier locomotives has been variously given[8,11,14] at figures between 0·80 and 0·92. The power factor of the supply to the traction substations may therefore be taken as being generally in the region of 0·70–0·80.

(3.6) Line Equipment

On d.c. electrifications, with few exceptions, the maximum line voltage in use at present is 3kV. This requires conductors to be generally in excess of 0·5in² equivalent copper section having regard to the combined effect that conductivity, substation spacing and the number of line paralleling points have on voltage drop. Since part of the line-work subjected to the greatest wear is the contact wire, it is desirable to provide as large a size for this as can conveniently be installed and maintained. A size frequently used by British engineers is 0·3in² cross-sectional area of copper or copper alloy. This contact

wire can be used on most d.c. projects, the remaining conductivity required being made up in the catenary or catenary and auxiliary catenary.

On a.c. electrifications where a high line voltage is practicable, considerations of voltage drop permit conductors of smaller copper section to be used. However, considerations of wear, corrosion, maintenance and useful life generally limit the minimum size of contact wire which it is advisable to use, 0·166 in² (107 mm²) being considered a satisfactory compromise. On some early a.c. railway electrifications a smaller contact wire was used originally, but 0·166 in² is being adopted for renewals. The minimum size of catenary necessary to support this smaller contact wire is again governed mainly by mechanical considerations, and consequently there is some freedom of choice of the material of which it is made. The weight of copper or copper-alloy conductors for a.c. systems may therefore be of the order of one-third or less of those used for d.c. systems, which results in an almost directly proportional saving in conductor costs. Additional savings are also possible because lighter structures and cheaper foundations may be used for support. Indeed it is possible, even on double track, to adopt single cantilever construction, which is cheaper than portal construction for these light loadings. When climatic and other conditions permit steel to be used for the catenary, the costs may be lowered still further because the conductivity margin may permit this.

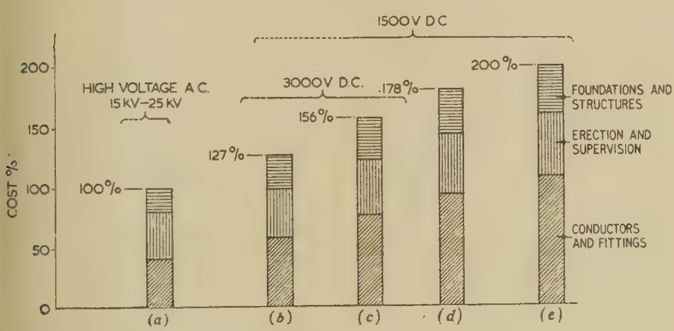

Fig. 4.—Relationship between component costs for different conductor cross-sections.

	Total actual cross-sectional area	Total equivalent copper section	Catenary	Auxiliary catenary	Contact wire
			Hard-drawn copper	Hard-drawn copper	Cadmium copper
	in²	in²	in (dia.)	in (dia.)	in²
(a)	0·24	0·21	7/0·116	—	0·166
(b)	0·50	0·45	19/0·116	—	0·30
(c)	0·69	0·63	37/0·101	19/0·080	0·30
(d)	0·87	0·81	37/0·116	19/0·109	0·30
(e)	1·07	1·00	37/0·136	19/0·124	0·30

Fig. 4, which is based on main-line project studies, illustrates the approximate relationship between line-work-component costs for five different conductor areas, and it shows that an a.c. system is appreciably cheaper than a d.c. one. In all these comparisons broad-flanged steel beam structures were used to support copper catenary and cadmium-copper contact wire without automatic tensioning. The cost of track bonding was included (under "conductors") in all cases except that of the 0·24 in² equipment, where it is unlikely that it would be necessary. There is little difference between the cost of line-work for high-voltage a.c. projects operating at between 15 and 25 kV, although the fittings may be a little more expensive as the voltage is increased because more insulation is necessary. At still higher voltages the weight of the additional insulation would influence structure and foundation costs.

The use of single cantilever construction, which is economically possible on a.c. projects, provides independent support and mechanically independent registration of the conductors. This facilitates maintenance by involving less interference with traffic, it provides drivers with a better view of signals and renders the installation less vulnerable to extensive damage after derailment. The lighter loading permits a wider choice of structure materials, e.g. indigenous timber and prestressed concrete, because the requirements fall within a more common production range. An example of this occurred on a recent oversea investigation when it was found that a local prestressed-concrete manufacturer possessed ready facilities for meeting structure specifications for a 25 kV system but not for a d.c. one.

Under favourable earth-conductivity conditions, track bonding will be unnecessary with high-voltage systems, or at the most, much lighter bonding will suffice. Also, the provision of an independent earth conductor is not so necessary in order to parallel the track on single-line sections. Electrolytic difficulties will not arise.

With a high-voltage a.c. system, annual maintenance expenditure tends to be less because the equipment is lighter; examples of this occur in structure painting and bond renewing. Finally, the ease with which an a.c. traction supply may be tapped with pole-top transformers, thereby enabling undeveloped districts to be "opened up" with a limited electricity supply, may be important. Particularly is this the case if minor power supplies are required along the route for station lighting, signalling and telephone repeaters.

(3.7) Structural Alterations for Line-Work Clearances

The work necessary to obtain satisfactory clearances for the overhead line-work and pantograph passages in tunnels, at over-bridges and near other structures, varies immensely on different projects. The cost naturally tends to increase as the system voltage is increased, but not proportionately so, because the clearances which it is prudent to allow for rolling-stock movement are the same for all systems. Reliable estimates for alterations to infringing structures can only be made if clear "go" and "no-go" dimensions are given. Experience has shown that, except for long tunnels, the total cost involved depends more upon the number of sites which require attention than it does upon the increase in clearance which has to be obtained at each site.

Views vary regarding the minimum distances to allow between live equipment and earthed structures for different voltages. High standards are often adopted or proposed where they can be easily obtained. Table 3 gives published figures for 20–25 kV projects. The figures allow for rolling-stock movement, i.e. lurching, spring movement, wear, etc., and for the effect of this on the pantograph "moving outline." These figures therefore include the clearances required for purely electrical reasons plus the effect of whatever margin it has been considered prudent to permit between the load-gauge profile and the maximum fixed-structure gauge; in short, the figures include a contingency allowance.

Minimum electrical clearances between live line-work and infringing structures will be the same as those adopted for the live portions of the rolling stock. Settling the economical vertical clearances is difficult because of the difficulty in predicting wire lift under the combined effect of equipment tensions and pantograph passages. The horizontal plane clearances will in all cases be governed by the limits set by the pantograph horns. Scope therefore exists for compromise between pantograph width and track-structure intervals, which govern the displacement of the line-work under influence of cross-winds. Con-

sideration of these factors may become important economically if many infringements exist.

The electrical clearances will depend first upon the nominal voltage and the transient values assumed; secondly upon atmospheric and climatic conditions, which are affected by such practical factors as the number of steam-locomotive passages and the tendency for air pollution in tunnels. Experience has shown that extreme transients, such as those arising from lightning, may be dissipated by means of horn gaps located on track structures at suitable intervals in vulnerable areas or by electrolytic-cell or capacitor types of arrester, and that the effects of minor transients, traction surges, etc., are usually displayed at dirty insulators. The authors can only suggest on present experience that the figures for clearances need not exceed those shown in Table 3, which have given satisfactory service, and that where special difficulty from sparkover is envisaged, experiments should be carried out. It is understood from French railway engineers that, as a result of recent experience and experiment, smaller clearances than those shown on Table 3 would be considered adequate for future construction. No figures have, however, been quoted.

Table 3

LINE-WORK CLEARANCES FOR 50 c/s PROJECTS

	mm	in
Belgian Congo: 25 kV		
Loading gauge—contact wire at maximum temperature—minimum	290	11·42
Loading gauge—contact wire at maximum temperature—desirable	400	15·75
France		
Savoy routes—originally 20 kV, but later raised to 23/25 kV		
Loading gauge—contact wire—minimum ..	300	11·82
Loading gauge—contact wire—desirable ..	370	14·58
Tunnel—catenary—minimum	400	15·75
Tunnel—catenary—desirable	500	19·70
Tunnel—pantograph horns—minimum ..	220	8·65
Tunnel—pantograph horns—desirable ..	325	12·80
Valenciennes–Thionville routes—25 kV		
(i) *Obstructions extending for some distance*		
(*a*) Mixed steam and electric operation		
Line conductors to earth (vertical)—minimum	370	14·58
Line conductors to earth (horizontal)—minimum	370	14·58
(*b*) Electric operation only		
Line conductors to earth (vertical)—minimum	320	12·61
Line conductors to earth (horizontal)—minimum	320	12·61
(ii) *Obstructions extending for a short distance*		
(*a*) Mixed steam and electric operation		
Line conductors to earth (vertical)—minimum	270	10·64
Line conductors to earth (horizontal)—minimum	220	8·65
(*b*) Electric operation only		
Line conductors to earth (vertical)—minimum	220	8·65
Line conductors to earth (horizontal)—minimum	170	6·70

It is impossible to generalize on costs, because route topography varies so widely. Examples of this were recently disclosed on two oversea main-line studies, neither of which traversed what are generally described as built-up areas. On these projects the estimates varied from as little as £35 per route-mile in the easier case to £5 300 per route-mile in the more difficult one, which included tunnels. These estimates were for a 10 in clearance to live line-work and the pantograph in both planes. It was, however, significant that the cost would be reduced by only about £1 000 per route-mile in the more expensive case if the figure of 10 in were reduced to 6 in, while the cost in the cheaper case would be unaffected by this change.

Consideration should always be given to alleviating action in order to meet special conditions. This may involve the protection of difficult sections with surge-dissipating equipment, the consideration of insulator design to meet special circumstances and the treatment of short tight spots by catenary diversion or other special arrangement.

(3.8) Telecommunication Interference

Open-wire telecommunication circuits which are parallel to and near a.c. track conductors are liable to interference by electrostatic and electromagnetic induction. These induced voltages may exceed the breakdown values normally associated with telephone equipment and even be sufficiently high to become dangerous to life. These circuits cannot therefore be permitted to follow the same route as standard-frequency electric-railway systems if parallelism is excessive. Apart from the danger aspect, the noise level induced in telephone circuits will be high in spite of frequent transpositions, on account of the difficulty of achieving and maintaining the degree of line balance on open lines which is necessary to eliminate it. Tests made on the 50 c/s electrified section between Mézières–Charleville and Valenciennes in N.E. France, where open-line communication circuits were specially retained for this purpose, revealed that induced voltages could exceed 1 kV when the separation distance from the traction conductors was some 10 m over a parallel distance of 5 km. Although this value fell rapidly to within safety limits as the spacing was increased, the noise nuisance remained even when the communication circuits were moved as far as 300 m from the traction conductors.

Harmonic interference injected into the traction conductors and supply network from rectifier rolling stock can also cause noise in telecommunication circuits, and this interference may occur at appreciable distances from the railway if open telephone lines parallel the distribution network feeding the traction system. Standard-frequency electrifications may be more troublesome in this respect than lower-frequency ones because of the higher fundamental.

While the interference problem is generally greater with a.c. than with d.c. traction systems, particularly from the danger aspect, d.c. systems are not exempt from this. Even rotary-convertor ripple voltage was disturbing in spite of attempts to counter it with filters or by coupling armatures to neutralize the pulses. Perhaps interference has become more of a problem in recent years as a result of improvements to telephone channels and equipment, which are now so good that previously accepted standards are hardly tolerable, even on railway circuits.

Of the two methods of countering interference, namely, moving the open lines and transferring the circuits to screened cables, the former course is not always practicable. Indeed bush country may make it quite impracticable or far too costly, having regard to maintenance difficulties and the absence of any return in the form of betterment or progress. If railway "omnibus" telephone circuits are cabled, the pulse-selective ringing feature may have to be converted to tone-frequency coding in order to avoid interference with other circuits within the cable. Provision may also have to be made to loop cabled "omnibus" circuits into trackside connection boxes spaced at mile intervals or less, so that the telephone facilities previously provided by open pol

lines are preserved. More repeaters will usually be necessary for cabled circuits, and power supplies will be required for these.

The cost of overcoming interference has been levelled as an objection to a.c. electrification, and while expenditure is necessary in this case, it is at least desirable with d.c. electrifications whenever the communication circuits parallel the electrified route.

The whole question of telecommunication interference must be considered in line with the development and betterment plans proposed by the railway departments and the Post Office if the latter's circuits are affected. Not infrequently it is found that both authorities have betterment plans in view, and cabling will merely accelerate these plans. Where this is so, part-payment arrangements become acceptable; indeed on one recent project it was found that by the time the electrification work could be completed most of the telephone interference problem on trunk circuits would have disappeared as a result of the abandonment of open lines for re-routed coaxial-cable channels and microwave radio links.

Significant amounts for cabling need not therefore always be included in electrification estimates; nor should the cost of this work be advanced as a deterrent to electrification. The ultimate "piping" of communication channels seems inevitable, and in many cases is long overdue. If some provision for this work has to be made in the electrification capital estimates, some annual credit seems admissible in respect of easier maintenance, improved reliability and the better expansion facilities offered by cabled systems.

(3.9) Signalling

The reliability of a railway signalling system must not be impaired by electrification. The method of immunizing it from the effects of traction currents, and the cost of doing so, will depend on the type of signalling in use and the system of electrification which is adopted.

Manual signalling systems will require very little modification for any system of electrification. More resighting of semaphore signals will usually be necessary with d.c. traction systems than with a.c. systems, because the heavier d.c. structures and linework are more liable to obstruct drivers' vision. On the other hand, with a.c. systems, greater precautions may have to be taken to earth frame and track interlockings, and metallic returns must be provided for block-and-token instrument circuits. These circuits may, however, be included within a screened communication cable.

Most electrifications require the running rails as conductors, and where track circuits are in use or proposed, discrimination must be assured between the signalling currents and the traction currents. This may be obtained on both a.c. and d.c. traction systems with most forms of coded track circuit, but it is likely that steady-energy alternatives would be used for new work instead of coded track circuit except where cab signalling is required.

When steady-energy track circuits are used on d.c. electrifications they must be fed with alternating current, and where both rails are required as traction conductors double-rail a.c. track circuits must be used. These require expensive impedance bonds because they have to be sufficiently large to carry the relatively high currents associated with d.c. traction; nor can bond size be reduced significantly for higher-voltage d.c. systems because, for a given train density, the track currents are not appreciably reduced on account of the wider substation spacing admitting more trains. If only one running rail is used as a conductor on d.c. traction systems (as on the Italian 3 kV system) permitting single-rail a.c. track circuit to be used and impedance bonds to be omitted, it may be necessary to parallel the continuous rail with an earth conductor. This will assist track conductivity and reduce rail current density which, at high values, may saturate the track-circuit equipment at the relay end.

On standard-frequency electrifications, steady-energy single-rail d.c. and single- or double-rail a.c. track circuits may both be used, provided that in the case of d.c. track circuits the rails are free from extraneous direct currents. These d.c. track circuits use a special d.c. track relay which is immune from standard-frequency traction currents. If the feed is from primary cells these may be choke protected, but if a rectifier is used at the feed end, precautions must be taken to prevent half-wave rectification of traction currents, which could cause a rise in the applied d.c. track voltage and affect the operation of the train shunt. Equipment has been developed for this purpose which does not depend on filter circuits for security. Where trickle-charged secondary cells are used to feed tracks, these may be charged and discharged with an automatic change-over device.

Wherever a.c. track circuit is used on a.c. traction systems the signalling-current frequency must differ from the fundamental and harmonics of the traction-system frequency, and a safe frequency discriminator must be installed at the relay end. It is possible to satisfy these conditions by incorporating a rectifier in circuit after the discriminator and using standard d.c. track relays. The feed ends may be supplied from local static frequency convertors, and compact 75 c/s equipment has been developed both here and abroad which is suitable for use on standard-frequency electrifications. Where double-rail a.c. track circuit is used the impedance bonds may be much smaller than those required for d.c. traction systems on account of the lower track currents.

Audio- or "musical"-frequency track circuit has been under development for some time, and has recently been installed on the standard-frequency electrification in N.E. France. This operates with 1 kc/s carrier modulated at 20 c/s. The high carrier frequency permits a reduction in the number of impedance-bond turns with some further saving in size and cost, although it demands a greater energy input owing to rail attenuation.

Where new track circuits are installed on standard-frequency traction systems there are therefore three alternatives to choose from, namely special single-rail direct current, single- or double-rail alternating current at suitable frequency and the "musical" track circuit requiring electronic equipment. The choice of modification to existing track circuits will be governed by their type. It is, however, significant that d.c. track relays, which are widely used on steam-operated lines, may be retained after standard-frequency electrification provided that the tracks are fed with alternating current. This will eliminate battery maintenance.

Electrification project studies, made by the authors, which included provision for new signalling installations as well as conversion of existing ones, revealed that the cost of this work was not affected to any marked extent by different traction systems.

(4) ECONOMIC CONSIDERATIONS

The justification for adopting the standard-frequency system of electrification must, of course, stand or fall upon its being the cheapest method of providing the necessary service. Having decided on the technical features required for any project, it is a matter of step-by-step procedure to estimate the costs of the fixed equipment and rolling stock for any system of electrification. As has already been mentioned, wide differences may be disclosed in the estimates for alterations to ways and works, depending on the topography of the line, while the distribution-system estimates may also vary depending upon the layout of, or the plans for, developing the power-supply system. In some cases the cost of providing transmission lines and even substations may be included

in the tariff charged by the electricity supply authority; in other cases (now not very frequent) the railway has to provide a generating station as well as substations and distribution system. Tariffs for the electricity supply will be influenced by the cost of coal or the availability of hydro-electric power, and when electrification is compared with Diesel operation, the cost of fuel may become the most significant factor.

In any economic comparison between electric and steam (or Diesel) traction the capital cost of electrification is greater than the other alternatives, but the annual savings in operation and maintenance may exceed the interest and depreciation charges on the higher outlay. However, when different systems of electrification are being compared, the differences between the operating and maintenance costs of each system are small. Consideration of the capital expenditures in each case, therefore, becomes the important factor.

Table 4

Comparison of the Annual Costs of Railway Electrification of a 300-Route-Mile Project with Different Systems

	1500 volts d.c.	3000 volts d.c.	$16\frac{2}{3}$ c/s a.c.	50 c/s a.c.
Power	11·5	11·4	11·7	11·8
Operation	22·8	22·9	24·4	22·5
Maintenance	20·2	18·8	18·1	17·5
Total (Running)	43·0	41·7	42·5	40·0
Interest	61·5	48·7	41·7	39·4
Depreciation	12·0	10·2	9·1	8·8
Total (Interest and depreciation)	73·5	58·9	50·8	48·2
Grand totals	128	112	105	100

Table 4 gives the annual costs on a comparative basis of four system studies made by the authors for a 300-route-mile project of low traffic density. The figures include allowances for changing the location of staff quarters and modifications to maintenance depots as required by the electric services. It will be seen that the difference in costs between the systems lies mainly in the capital charges and that the operation and maintenance totals vary only a little, and even then in the same direction as those of the capital charges. These studies disclosed that, for the project in question, the standard-frequency system is 12% cheaper than the nearest d.c. alternative (3 kV) and 28% cheaper than 1·5 kV d.c. These results arise almost entirely from differences in capital cost of track equipment and substations, which together comprise nearly half the total and which are 50% more expensive than in the a.c. alternative. The only item for which the a.c. alternative is the more costly is for alterations to ways and works, where it is 12% dearer.

The authors have not had occasion to make a project study of an existing main line having a high traffic density, but it seems likely that the standard-frequency system will be the cheapest method of electrification in this case also. Although the quantity of rolling stock will increase corresponding to increases in traffic density, the unit cost of locomotives is just about the same for alternating and direct current; rolling stock costs would not therefore affect the comparison, whatever the traffic density. Of the fixed equipment, the number of substations will tend to increase with an increase of traffic (although by no means in proportion), but the cost of a.c. substations will still be less than d.c. ones. The cost of track equipment depends rather on the single-track mileage to be equipped than on the traffic density, but the a.c. alternative is always much cheaper. As already mentioned, the only item which handicaps the a.c. system is the cost of the alterations to ways and works. The amount of this depends on the number of tunnels, bridges, etc., which infringe the required clearances, but the difference in favour of direct current seems likely to be small, and in neither case is this expenditure affected by increases in the traffic density. These views are supported by the published results of a French study embracing a group of routes of average traffic density of about nine million ton-miles per annum per single-track mile.

Finally there is one matter which has perhaps not been squarely faced in comparing the estimates, namely the question whether, with d.c. electrification, it is necessary to cable the communication circuits if these are open-wire lines. Views on this have already been expressed, but it has to be admitted that it is theoretically possible to use open lines in the d.c. case. However, even an expenditure of some £5 000 per route-mile on this account would still not have been sufficient to tip the balance in favour of direct current in the low-traffic-density projects discussed. Its effect would be less significant still in a high-traffic-density case.

It is not inferred that this relationship between traffic density and system of traction may be applied with impunity into the suburban range, where trains have to be run at the shortest possible headway for which the line can be signalled. Under these conditions, for security reasons, it is prudent to increase the capacity of the fixed equipment, particularly the substations beyond electrical requirements; this will reduce the margins. Alternating-current multiple-unit stock may be more costly than the d.c. version, particularly if limitations are imposed by gauge, platform height, or axle loading. Also, expenditure on rolling stock is likely to form a much larger percentage of the total cost because sufficient multiple units must be purchased to operate the peak traffic, and their utilization may therefore be poor compared with that of locomotives working a main-line service. Furthermore, in built-up suburban areas the cost of the distribution system may be increased by the necessity for cabling, and the ways and works modification costs are almost certainly likely to be increased by the existence of tunnels and overbridges, even to an extent that a current-rail system becomes imperative.

At the other extreme, where traffic is very light and especially i[f] conditions will not permit the working of large annual locomotive mileages which are possible after electrification, the operating and maintenance economies resulting from electrification may be swamped by the capital charges in respect of the fixed installation. In such a case, even electrification at the standard frequency could only be justified, if at all, as a means of facilitating through working and thereby increasing the savings on neighbouring lines which had already been equipped for electric operation. When this does not apply and traffic is very light, consideration must be given to Diesel working as an alternative to electrification, even if only as an interim measure.

The fact that standard-frequency electrification is cheaper than alternative systems has a major bearing on the question whether or when it will pay to electrify rather than convert t[o] Diesel operation. High traffic density favours electrification because more rolling stock is required, and, for a given performance, Diesel rolling stock is more expensive than electric. With low traffic density the high cost of the fixed equipment militates against electrification, but since this cost increases only slowly with increasing traffic and the operation and maintenance costs are no greater with electric than with Diesel traction, there exists a traffic density at which the total annual costs (including capital charges) of the two forms of motive power will be equal. It is not possible to generalize on the traffic density at which th[is] will occur, since it involves, among other things, the price o[f] Diesel fuel and tariffs for electrical energy, both of which vary widely for different circumstances. In one investigation mad[e]

by the authors the costs balanced at about eight million trailing ton-miles per annum per single-track mile, while in another it was about half that figure. In both cases the figures would have been much higher with d.c. electrification.

Apart from the issues discussed, the overall economic aspect must be considered in relation to the need to step up efficiency by increasing track capacity. Electrification in combination with suitable signalling can contribute far more in this respect than any other form of traction. As a national policy in order to conserve coal or to utilize hydro-electric or atomic sources of power and to avoid substantial increases in oil imports, railway electrification requires no justification; it should be proceeded with as quickly as possible. Wherever electrification has been introduced the operating departments and the public have been appreciative of the services and the amenities it provides.

(5) ACKNOWLEDGMENTS

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DISCUSSION BEFORE THE INSTITUTION, 2ND FEBRUARY, 1956

Mr. C. M. Cock: As so much interest is now being shown in the high-voltage standard-frequency system of railway electrification, a British paper on the subject is opportune and very welcome. I share the optimism of the authors, but it seems that this system introduces yet another and a strong contestant in the so-called battle of the systems. The standard-frequency system has definite technical advantages; it includes high voltage for the contact line, simple and cheap substations, and it can include the well-tried d.c. traction motor. The advantages are explained in the paper and are indisputable.

I am in entire agreement with the authors' views on the d.c. traction motor. It is becoming increasingly evident that this type of motor fed by rectifiers, either mercury-arc or possibly semi-conductor, will emerge as the best arrangement for standard-frequency traction. In fact, in this country about five years ago, when the Lancaster–Morecambe–Heysham electrification was being planned, the rectifier-fed d.c. motor was adopted.

Nowhere in the paper is there a firm recommendation by the authors, but there is an inference, or rather more than an inference, in their closing remarks that standard-frequency main-line electrification is, in general, cheaper than any other, except for a suburban project. It can be so for a particular case, but I suggest that there can be no generalization; each project must be examined in detail and decided on merit.

Table 4 in the paper relates to a 300-mile project with low traffic density and, I think, single line. The crux of the matter is in the grand totals, in which the capital costs are by far the most important. I do not doubt their accuracy, but I know of another oversea project which has been investigated recently, of 400 route-miles of single track with a traffic density of nearly 6 000 000 trailing-ton-miles per mile of single track per annum, and I should like to compare the results obtained with those in Table 4. In the 400-mile project, the ratio of the annual costs of the d.c. to the standard-frequency systems of electrification, omitting the important item of telecommunication, were 105 : 100, as compared with 112 : 100 in Table 4. In the paper it is stated that the capital cost of track equipment and substations is about 50% greater with direct than with alternating current. In the 400-mile project this difference was found to be 30%. Both the d.c. and the a.c. schemes in the 400-mile project were burdened with the cost of very long e.h.v. transmission lines, so that this item cancels out. The cost of putting the telecommunication circuits into cable is a very heavy charge on the a.c. system and makes a big difference to the capital charges. If it is debited to the a.c. system the difference in the annual costs between direct and alternating current for the 400-mile scheme is negligible, so that economically there is nothing to choose between the two systems.

I think that, in this respect, the authors' argument on this controversial subject in Section 3.8 of the paper is too unfavourable to direct current and rather inconclusive. It is axiomatic that open-wire communication circuits paralleling and adjacent to the railway will not work with a.c. electrification, and cabling is essential. On the other hand, cabling has not been necessary

with d.c. electrification; for many years past open-wire communication circuits have been made to work satisfactorily alongside d.c. contact lines of 3 and 1·5 kV in Italy, South Africa and India. The fidelity of the speech and signals may not be up to the standard of perfection to which the authors rightly aspire, but it is sufficiently good to be acceptable. The interference from substation rectifiers or rotating convertors can, by suitable means, be reduced to a negligible level.

The French claims for superior adhesion of the 50 c/s ignitron locomotive are accepted, but, of course, it cannot be ignored that a d.c. convertor-type locomotive could also produce similar qualities if provided with smooth notching control and parallel-connected traction motors. Although an a.c. B_0–B_0 locomotive was included in the study for the 400-mile project against a d.c. C_0–C_0 locomotive, the difference in cost between the two types was only 4·5% in favour of alternating current, in spite of the greater bulk and weight of the d.c. locomotive. It must be obvious that, in the case of alternating current, the cost of adding a transformer and rectifiers, or in other words putting a substation into a locomotive of the B_0–B_0 type, will absorb a large part of the savings resulting from the reduction in size and weight of the mechanical parts and in the number of traction motors. Another point for consideration is that there may, in some cases, be conditions of load and other factors under which the d.c. B_0–B_0 locomotive with four axles would provide sufficient adhesion for the job in hand. In this case, the a.c. counterpart would be 11% more expensive and therefore make the case more favourable to d.c. electrification.

Very little expenditure was required in the 400-mile project for providing additional clearances for the contact lines at bridges and tunnels, which is a point in favour of alternating current. After consideration of all the conditions and circumstances there was very little difference between 3 kV d.c. and standard frequency. As a matter of fact, the conclusion reached was that Diesel traction would be more economic than electrification.

I would emphasize my main point that there can be no generalization as to the most suitable system of electrification even with all the attractions of a standard-frequency supply. Each case for electrification must be studied in detail and assessed and decided on merit.

In view of the prominence given in the paper to the d.c. motor, it would be of assistance to the student if particulars could be displayed against the a.c. counterparts in Fig. 1.

Mr. S. B. Warder: In 1954 an International Railway Congress was held in London, and I reported on those characteristics of a railway system which led to the choice of the ideal system of electrification. To assess those characteristics I circulated a questionnaire to the other railway undertakings designed to elicit suitable information on which some conclusions could be based. One of these questions was 'If you were able to change your system and start *de novo*, what would your choice be?' All the replies were 'We wouldn't change'. In the subsequent discussions the French Railways hedged a little and said 'It all depends. We have a new system which we think is going to be the best', but they did not convince all the other railways, and the only conclusion reached was that the 50 c/s system showed great promise and found its best application on lightly-loaded lines.

One year later we were all invited to Lille by the S.N.C.F. and shown the 'proof' which was not forthcoming earlier. We were all very impressed. The new element was the increased adhesion of a.c. locomotives as compared with d.c. locomotives, and the French Railways are entitled to much credit for producing that result. All the observers were sceptical. The a.c. countries said with some justification that it was no better than they could do—after all, the same result could be obtained with mechanical coupling. The d.c. countries said 'Our conditions are different'. I mention this to show that it is not enough to prove one's case by an attractive exercise. It is still more difficult to justify the particular by the general application. While, therefore, I have the greatest respect for the authors' ability and knowledge of this subject, the railway undertaking as a rule knows what is best for its own conditions.

The British Transport Commission decided in 1950 that the standard system for British Railways should be 1·5 kV d.c., but where conditions were suitable there was no objection to using any of the other systems mentioned by the authors. At that time certain projects were nearing completion and new ones were being worked out. In 1951 we embarked on the Lancaster–Morecambe–Heysham experiment, which basically was intended to obtain some experience on a rectifier-powered train. Subsequently we have extended the experiments to include single-anode rectifiers, and recently a germanium rectifier has been tried and put into service.

We could not avoid noticing what was going on abroad, and consequently we have carried out a complete study of the problem anew, but in this case not a paper study but a factual study of every technical aspect involved. We have consulted all the people who should be consulted; we have surveyed routes and made a thorough job of it. The conclusions of that study will be announced shortly.

I am afraid that I cannot endorse the authors' views on inter-running between a.c. and d.c. systems. We have been into this matter very exhaustively, and it is not worth the trouble. Nobody thinks more highly of the Southern Region third-rail system than I do, but I am also now much more conscious of its shortcomings. A third-rail system is very convenient, provided that it is confined to multiple-unit passenger trains and that its area can be permanently restricted. It has proved impossible to restrict the Southern system, and it must go on as far as Dover and Ramsgate to secure the full benefits of the existing installation; but for traffic other than multiple-unit trains the difficulties become increasingly complex. If it is necessary to retain an existing third-rail system then with certain qualifications it must remain independent, and a separate contact system must be faced if an a.c. system is contemplated. If the suburban system operates on an overhead contact wire it is necessary to consider whether it is not worth while to convert all the trains rather than contemplate complicated dual-fitted stock.

On the question of locomotives, I agree with the authors that the rectifier offers the best solution which is available at present. British manufacturers should be particularly favoured in this respect because of the various types they have to offer.

As to adhesion, opinions will differ so long as no information is available. Obviously the possibility of increasing it is important, because it offers not only more power at the wheel for the same weight but also less weight and therefore considerable savings in initial track costs and maintenance of the track.

The paper would be more effective if it included some information to show that the reduced amount of material required for the overhead system reduced the amount of maintenance work. The extent to which any saving is possible in this direction is very important, and particularly saving in time because of the possibility of doing work on the live d.c. 1 500-volt system.

Finally, there is the question of telecommunication interference, on which I agree with the authors. Obsolete methods have prevailed for too long, and their modernization has had to be paid for out of electrification costs. Modern conditions demand the best methods of communication, and this means cables. My experience is that, in general, open-wire circuits on any d.c. or a.c. overhead line are unworkable at some time or other, and in view of the importance of the communication system and o[illegible]

duty to the public we cannot take any risks. We must have the best and most reliable communication circuits to ensure that orders are transmitted with speed and accuracy.

Monsieur J. Gastine (*France*): Table 1 does not mention two important electrifications of the S.N.C.F. The first, known as Nord–Paris, is under construction and will be put into operation within two years. It consists primarily of the Paris–Lille line, which carries a very heavy traffic, including very fast passenger trains and very heavy freight trains. The length of route is about 550 km and the number of locomotives required about 100, most of which are now on order. The other electrification, Est–Paris, includes the main line from Paris to Nancy with a junction at Sarrebourg with the Thionville–Reding–Basle electrification now being equipped. The preliminary studies for this have been completed and the project will be submitted in the near future for the approval of the Administration. The length of route is over 660 km and the number of locomotives which will have to be ordered is about 150.

When these schemes are carried out, the total length of route in France electrified at the standard frequency will be 2 450 km. On the other hand, the total length of the lines electrified at 1·5 kV d.c. is about 4 200 km. In the very near future, the length of the S.N.C.F. lines electrified at 50 c/s will reach about 60% of the length of the lines electrified at 1·5 kV d.c.

The second question concerns the choice of the types of locomotive. Experience on the Valenciennes–Thionville line has shown the excellent performance of the ignitron locomotives, and our fears of trouble arising from the current harmonics generated by these machines have been allayed as the result of considerable experience on the Valenciennes–Thionville line.

This has led us to order, for the new electrifications, almost exclusively B_0–B_0 rectifier locomotives with ignitrons or excitrons. This type has been adopted both for high-speed locomotives (maximum speed 160 km/h) and for mixed-traffic locomotives for passenger trains (maximum speed 120 km/h) and for goods and freight trains. Moreover, the excellent adhesion qualities of this type have induced us to design a new type—a lightweight B_0–B_0 locomotive the weight of which is less than 60 tons and the performance of which is the same as that of the existing 80-ton B_0–B_0 1·5 kV d.c. locomotives. These are able to haul 550-ton express trains on the level at a speed of 120 km/h and 1 350-ton goods trains on gradients of 8 in 10^3. Our future orders of locomotives for the Nord–Paris and Est–Paris electrifications will be almost exclusively for this type. Electric locomotive prices being approximately proportional to weight, the new design of light-weight locomotive will allow substantial savings to be made.

The third question concerns the clearances for the overhead-line work and pantograph passages. In the case of lines with numerous tunnels and overbridges, the costs of the electrification are affected to some extent by the width of the clearances. A careful study has made it possible to reduce the clearances given in Table 3 of the paper for obstructions which extend for some distance. The figures of 370 and 320 mm will be reduced in the international standards of U.I.C. to 320 and 270 mm, respectively, which represents a reduction of 50 mm, or about 2 in.

Fig. 1 compares $16\frac{2}{3}$ and 50 c/s commutator motors designed for similar duties, and the authors show an increase of weight of about 35% for the 50 c/s motor. With motors of recent design the increase of weight is only of the order of 10–15%. On the other hand, the size of these motors has been reduced sufficiently for them to be easily accommodated within the limited space usually available for multiple-unit equipment. We are now studying 50 c/s multiple units for suburban service with the mechanical parts of 1·5 kV d.c. multiple units existing in service. They will have commutator motors or d.c. motors with rectifier, and will offer the same possibilities as the d.c. multiple unit.

Mr. O. J. Crompton: Type (*c*) in Fig. 4 closely resembles the size of copper section adopted by British Railways for their latest d.c. scheme between Shenfield and Southend. The authors show this as costing 56% more than high-voltage a.c. electrification, and they also show the 1·0 in² equipment, type (*e*), as costing twice as much as the a.c. equipment. I agree that the figures are about correct for the conditions which they assumed when making their calculations, but it is unfortunate that these conditions are not clearly stated in the paper. The figures are based on copper at a price of £285 a ton, and also—and this is most important—they are based not on a complete scheme but on a mile of single-track open-route main line.

At £400 a ton the margins in favour of alternating current in Fig. 4 would be even greater than those which the authors show, but the fact that the figures are based on single-track main-line construction is very important; if the main line were double track the a.c. costs would be doubled, but the d.c. costs would not be doubled; for the heavier equipment a portal structure would be cheaper than two cantilevers. Again, an average scheme in this country would include some terminal stations and large junctions. The margin between alternating and direct current is much smaller there than on the open route, especially if there is to be a large amount of electrical sectioning.

Another point to be considered is that the figures given in the paper are for fixed d.c. and fixed a.c. equipment. That is a fair comparison only for slow-speed railways. For higher speeds, while automatic tensioning may not be necessary with the heavier d.c. equipment it will be considered by most people to be essential with the lighter a.c. equipment, and that will reduce the margin still more. I believe that the figure for type (*c*) would then be only 125–145%, depending on the nature of the scheme and the price of copper. Thus, while the authors' figures are quite fair for copper at £285 a ton and single-track main line without large stations and junctions, and for fairly low speeds, I consider that the margin in favour of alternating current will be very much smaller for schemes in this country.

Mr. F. J. Lane: Electrification at the standard frequency implies that the load would be taken from the public supply system. The way in which this is done must take account of a number of factors mentioned in the paper as follows:

(i) The proposed catenary voltage of 25 kV.
(ii) Solid earthing of one side of the supply to permit earth return.
(iii) The violent load fluctuations to be expected.
(iv) The single-phase nature of the load.
(v) The harmonics caused by the rectifier locomotive.

The first two factors indicate the necessity for an interposing transformer, since 25 kV is not a voltage used for other purposes in Great Britain and solid neutral earthing is not usual in this voltage region even if one of the existing supply voltages could be used.

The last three factors all indicate the importance of segregating the traction load from the normal distribution supplies, and their effects will be minimized by taking the supplies from what the paper refers to as 'strong' points of the system.

The Scott-connected transformer seems to involve complications in equipment design and system arrangement, and may accentuate the difficulties arising from the harmonics.

On the whole, therefore, it would seem reasonable to adopt a method of connection whereby the supplies are taken directly from the 132 kV system as illustrated in Fig. A.

Mr. F. Whyman: I am an advocate of a.c. electrification wherever it can be economically justified, but I feel that the authors have been a little imprudent in underestimating the difficulties associated with 50 c/s traction, particularly in what

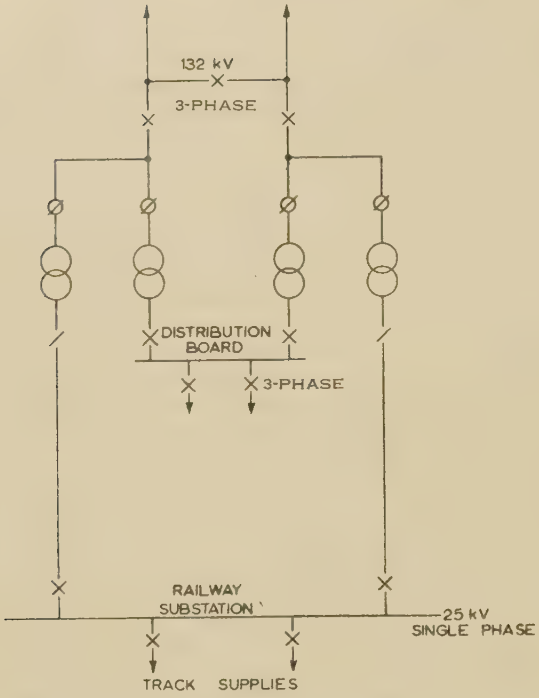

Fig. A.—Typical railway supply from 132 kV system.

they refer to as 'bush' country. In the last paragraph of Section 3.1.1 there is a reference to the usual red herring, that there are objections to 50 c/s traction motors on the grounds of an unavoidable increase in unsprung weight if they are axle-mounted. Can the authors produce any evidence in support of that statement?

In Section 3.1.3 the question of adhesion with d.c. rectifier-fed locomotives is not properly stated. One of the big advantages comes from using motors in parallel rather than in series, but a still greater advantage comes in not having resistance in series with the motor breaking down the line voltage during starting, but in having a constant-voltage source of direct current on any given notch. In that connection, in Section 3.2 the authors refer to inter-running with alternating and direct current, and suggest that the resistance control provided for the d.c. system might be used instead of transformer-tap control when on a.c. territory. That would remove much of the advantage of adhesion inherent in a.c. traction.

One of the major points on which I disagree with the authors is in Section 3.3, where it is stated that it is usual to design substation spacing so that there is a 20% voltage drop under normal conditions. That would be desirable if it could be had for nothing, but in my experience it is totally unnecessary. As an example, some 3 kV equipments supplied some months ago for a d.c. system which is being changed over to 3 kV have been running for many months quite satisfactorily on 1·5 kV, waiting for the change to be made, and no trouble has been experienced in spite of fluctuations of considerably more than 20% in the 1·5 kV system. There is thus no difficulty in making rolling stock suitable for operating down to low voltage. The authors suggest that there may be difficulties with auxiliaries such as brake exhausters or compressors. I think that the answer is to design them so that they will work down to 25–30% of the line voltage.

I think that the authors are also wrong in their reference to the cost of d.c. and a.c. locomotives. For locomotives having the same number of axles, the a.c. locomotive is inherently more expensive and must remain so; the only advantage which can be obtained, in perhaps half the applications, is where a 4-axle locomotive can be used with alternating current as against a 6-axle locomotive with direct current.

There has also been wishful thinking in regard to telecommunication. We have found that it is impossible to 'wish' the difficulties away; they arise particularly in 'bush' country, where much of this a.c. electrification has its application, and they represent a very large part of the cost.

A final point which is little appreciated, and which particularly refers to under-developed countries, is that the transmission-line requirements to supply 50 c/s substations are, for the same voltage drop, doubled with alternating as compared with direct current. For a 3 kV system recently investigated, an 88 kV transmission line has been envisaged to supply all the d.c. substations with reasonable voltage drop; but to provide the same voltage drop to a.c. substations feeding an overhead wire for rectifier-fed d.c. motors would require two exactly similar transmission lines in parallel. That is one of the disappointments which lie in our way if we underestimate the conditions in under-developed countries.

Mr. A. W. Manser: I feel that the question of dual systems of rolling-stock equipment is being treated rather lightly. Technically it is, of course, quite possible to arrange for rolling stock to take its feed from two different supply systems. It would be even more interesting to arrange to do it from three different supply systems. But someone has to maintain the equipment and the more components that are put into a vehicle the less reliable it becomes, the reliability being in inverse proportion to the number of components. However good the equipment may be, if there were only half as much it would fail only half as frequently.

This applies to the a.c./d.c. type of dual equipment and to the dual a.c. equipment to which the authors have not referred. On the basis of the figures which the authors have quoted for structure alterations, it is attractive to pay £5 000 a mile to dispense with the complication of dual equipment, which I believe will prove a very expensive bogey—though probably not a very obvious one. In the main, the passenger wants to get from one place to another reliably, and I am sure that the simpler the equipment the more reliable will be the operation.

In Table 4 there is a statement of relative costs. From what source do the authors obtain their figures for maintenance of the 50 c/s a.c. system? They state it with some degree of precision—17·5, as against 18·1 for the $16\frac{2}{3}$ c/s system. I assume that this is for rectifier stock, because general interest centres on that type of stock, but I do not think that anyone has had this type of equipment in service in bulk for long enough to be able to state the cost of maintenance. The authors may state that the maintenance of the rolling stock is not the most influential component of the total maintenance cost, and on that matter I could not argue with them. It may well be that they have deduced this figure from other equipments, d.c. and a.c., but it seems that it is rather a fine comparison to make if the figures are being so deduced.

Mr. W. B. G. Collis: D.C. traction designers have tended to become more isolated than their colleagues in other fields of application. With the advent of standard-frequency traction they must learn to respect the wealth of experience which transformer, switchgear and rectifier designers can offer from their own particular fields. In turn, those designers must become receptive to suggestions from traction engineers for mechanical adaptation of their products to meet the severity of rolling-stock conditions and the very high standards of railway reliability.

For standard-frequency traction, the problems of telecom-

munication and traction must become better mutually understood by both parties. Recently, there have been several false appreciations of the interference problem.

The effect of commutation ripple from rectifiers mounted on rolling stock may well be over-estimated. Although the amplitude may be as much as 20% at the rectifier, the intervening transformer will reduce this to only 1–2% at the line. With the semi-conductor rectifier, the duration of the commutating period is brief, whilst the ripple frequency can be adjusted by the introduction of a suitable *RC* circuit as needed to avoid critical communication frequencies.

The transformer mounted on the vehicle brings advantages as well as difficulties of accommodation. Not only does it suppress commutation ripple when referred to the primary voltage, but with the increasing adoption of low-voltage control and tap change, it will perform the same function for switching interference. There is also the valuable cushioning effect in both directions between the traction motors and the line.

Finally, there is the advantage of a wide choice of different voltages, both alternating and rectified direct, for all the many locomotive and train requirements.

Mr. C. C. Inglis: It has been said that 'history does not repeat itself but only historians'. However, it is useful to look into the past, and I remember that, after the First World War, considerable electrification activity took place all over the world, and of the many projects, I give two instances. In one case, immediately after the project was put into service the world financial slump occurred; traffic dropped and its economic justification vanished. In another case, engineering capital estimates were exceeded, and again the economic justification largely disappeared.

Nevertheless, nobody would say that these schemes were not well worth while. In one case extensions were put in hand, and in the other, a high official of the railway concerned said that they could not possibly have carried the war-time traffic by steam.

I quote these cases to indicate that the original economic justification is not the only consideration.

If we examine the relative figures of cost for the various systems of electrification, I cannot believe that the differences are very significant, and that by and large there is sometimes nothing much to choose on economic grounds. We must therefore turn to other considerations for help, and these must be the imponderables. I define them as follows:

Reliability.
Capability and susceptibility of technical improvement.
Flexibility in service.
Suitability for extension at minimum cost.

Dr. J. M. Kay: The authors have put forward an impressive case for the 50 c/s high-voltage traction system, and for the rectifier-fed locomotive in particular. Tribute should be paid to the work of the French railway authorities, for it is certain that, without the full-scale demonstration of 50 c/s traction on the Valenciennes–Thionville route, the full potentialities of the various 50 c/s locomotives could not have been established.

A remarkable result to emerge from the French demonstration has been the haulage capacity of the relatively small B_0–B_0 rectifier locomotives. It is significant that this type has been chosen exclusively for the extension of the 50 c/s system on the Paris–Lille main line. A B_0–B_0 rectifier locomotive designed for mixed traffic work with a rating of 1 800–2 000 h.p. would appear to meet nearly all the traffic requirements of the British Railways system. However, for heavy freight traffic, particularly on heavily graded lines, a rotary-convertor type of locomotive has certain advantages, especially in regenerative braking.

The rotary-convertor design is feasible only with a locomotive of larger dimensions, i.e. using the C_0–C_0 wheel arrangement; but if the 50 c/s system were adopted throughout the country, this type might well be required on certain lines.

A comparison of costs between the 50 c/s system and a d.c. system can only be made for particular routes, but it does appear that, in this country, the difference in capital costs between different systems will often be marginal. When this is so, the main advantage of the 50 c/s system will lie in the superior hauling capacity and starting performance of rectifier locomotives.

An argument has been advanced periodically that delay would be incurred if a new system were adopted for railway electrification in place of 1·5 kV d.c. Hopes will be raised, however, now that the British Transport Commission has reached a decision.

Mr. J. H. R. Nixon: There is a natural tendency to apply the findings of the paper to conditions on British Railways and the C.E.A., but this is a general paper and not applicable to any particular system. There are many manufacturers and consultants who have to advise oversea clients on the best system for their particular conditions. The authors write of territories under British influence which have in former times, no doubt acting on the best possible advice, electrified on d.c. systems. Those territories, however, are looking at developments in the United States, France, Germany and elsewhere, and they will naturally want further advice on the subject. It is imperative, therefore, that our manufacturing industry and consulting engineers should have knowledge and experience of this subject.

It is no criticism of the paper to state that it consists of generalities. A detailed justification of every comment made and every conclusion reached would naturally take too much space. I suggest that the paper calls for supplementary studies to be made, which may perhaps form the subject of further papers. For example, most speakers are firmly in support of the conclusion that rectifier locomotives are the best form to use if 50 c/s electrification is accepted. I think that is true, and there is no doubt that the rectifier locomotive is only at the beginning of its development, while the conventional d.c. locomotive is at an advanced stage of development. We must not, however, dismiss the motor-generator converting unit lightly, because it can offer some advantages in power-factor correction and in regeneration. It could be used with squirrel-cage driving motors instead of direct-current machines. These are factors which need to be studied in relation to each other and to substation practice. It could affect the distance between substations. I suggest, therefore, that a detailed and critical study needs to be made of the relative forms of locomotive before it is possible to reach a conclusion which can be regarded as final, in regard not only to the locomotive but to the supply system and the substation equipment.

It is true that rectifier locomotives have their substation in the locomotive. However, that is a simplification, because the stationary equipment is relatively simple, and therefore heavy loading can be applied on the system through simple and light substation equipment. That leads to the question whether, if this kind of electrification could be applied throughout this country immediately, the power resources of the country could cope with it. Will developments keep in step? Is this system, if applied to this country, going to make a demand on our coal resources which can be met? There may still be scope for Diesel-electric locomotives.

If I were asked what was the best service that British Railways could confer on the manufacturing industry of this counrty, I would state that it would be the speedy transport of goods. Would it be possible to consider, under a system of 50 c/s electrification, a heavier density of loading by express goods trains at night, and so ease the load factor problem of the C.E.A.?

Mr. J. R. Harding (*communicated*): In Section 4 of the paper, the authors mention £5 000 per route-mile as a typical cost for

replacing open-wire telecommunication circuits by cable, and they add that this cost, even if it is fairly chargeable only to the a.c. scheme, would not have been sufficient to tip the balance in favour of the d.c. scheme in the typical comparison in this paper. It seems clear from the remarks of Messrs. Cock, Warder and others that, in some cases, the overall cost comparison between the two alternatives may be so close that the charging or otherwise of this item might well be the deciding factor. I would therefore ask the authors for a little more information on this estimate. Presumably it was based upon normal lead-sheathed and armoured cables, either laid direct in the ground or carried upon reinforced-concrete line side posts, and was based on the assumption that a single cable only would be required. In practice, however, there may well be a need for a power-supply cable for signalling purposes, even though this might not be regarded as coming within the cost of the electrification scheme as such. However, if cabling of communication circuits is part of a d.c. scheme, the extra cost is little more than that of the supply and installation of the cables themselves, since the cable route exists for the power feeder and pilot and supervisory cables, whereas, in the case of the a.c. scheme, there is the additional cost of providing a route for the communication cables themselves and for power cables for signalling purposes if required.

Under these circumstances the type of route hitherto employed might well not be the most economical proposition, bearing in mind the availability of aluminium-sheathed cables or stainless-steel-sheathed cables, the latter being particularly suitable for railway conditions. One such installation has already been carried out in Australia, where the cable is carried on the overhead contact line structures, and shows a saving of the order of £2 000 or £3 000 per mile as compared with the normal underground cable. It therefore seems important that these types should be borne in mind when making comparisons in any individual case.

It seemed to be assumed by speakers that, if open-wire circuits are replaced by cable, the effects of induced voltages are reduced to an acceptable level, but from preliminary studies it seems doubtful whether this will be so and that it may well be necessary to employ isolating transformers between the cable conductors and connected apparatus. However, this is already established practice in the case of pilot cables on overhead transmission lines and is not likely to lead to any serious technical difficulties.

Prof. E. W. Marchant: (*communicated*): In 1934, when there was widespread unemployment, The Institution sent recommendations to the Government that railway electrification should be undertaken on a relatively large scale. Had these recommendations been adopted, the condition of the railways at present would be very different, and the work of electrification would have helped to relieve unemployment and have saved the many millions of pounds paid out to men for doing nothing. I hope that the schemes now being considered will come into operation with as little delay as possible. The possibility of high speeds with electrically driven coaches was demonstrated in the Berlin–Zossen trials early in this century. I used to exhibit a slide of a 3-phase rail car with overhead lines and bow collectors running at 200 km/h. At the same time it should be emphasized that increase in speed involves greatly increased wear and tear on the track, and in this country it is difficult to justify.

Mr. L. F. Scantlebury (*communicated*): The prevention of interference to telecommunication circuits is not such a straightforward matter as the paper would suggest. It is true that electric induction on overhead circuits can be prevented by placing them underground in cable, and to cater for this and other adverse effects the French Administration has prohibited overhead lines within a band 150 m in width on either side of electrified railways. But electromagnetic induction is not necessarily eliminated by cabling. The lead sheath affords screening depending on its size and thickness, and if the cable is also armoured, additional screening will result. However, if the induction is high, as will be the case when cables are parallel to h.v. a.c. electrified railways for several miles at close separations, the screening may not be sufficient to reduce longitudinally induced e.m.f.'s and the resulting noise to acceptable limits. In this country service telephone cables are practically all lead-covered without armouring or other additional screening, and investigations carried out by the Post Office show that high longitudinal induced voltages will inevitably arise, especially where railways entering towns and cities run parallel to roads and special measures will need to be adopted.

The authors have referred to the possibilities of danger and induced noise, which can be dealt with by applying the measures normally adopted to avoid interference from power lines. However, there is a further aspect and one of particular importance to the Post Office, namely disturbance to telephone switching systems. The bulk of the signalling between exchanges in this country is by direct current with earth connections, and these systems will not work if induced longitudinal e.m.f.'s exceed a few volts. Such circuits in the proximity of h.v. a.c. electrified railways, even in cable, would definitely be affected, and palliative measures would be essential, such as conversion to a.c. methods of signalling. In view of the numbers and varieties of circuits involved, this would involve the Post Office in considerable redesign of equipment, and the conversion would be expensive and would take time to carry out.

A considerable amount of the Post Office plant likely to be affected is in rural districts where underground cable could not normally be justified, while in towns and cities most of the external plant is already underground. It would not be wise, therefore, to assume that the cost of preventing interference to telecommunication circuits would be affected to any great extent by Post Office plans for the extended use of cables.

[The authors' reply to the above discussion will be found on page 430.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 13TH FEBRUARY, 1956

Mr. J. E. Davison: It is particularly opportune that the authors have presented the paper at the present time, in view of the British Transport Commission's recent investigation into whether to use a.c. or d.c. traction for the Euston–Manchester and Liverpool lines. No public announcement has yet been made as to which system is to be adopted for this scheme or indeed for all future electrification in Britain.

I agree that, of the three methods of utilizing alternating current at 50 c/s for rail traction, i.e. 50 c/s motors, motor-generator sets and rectifier equipments, the latter offers the best characteristics and performance from a railway point of view. The ability to utilize the well-tried and proved d.c. traction motor with its inherent robustness, simplicity and ideal torque/speed characteristic for starting makes the rectifier method the most attractive for rail use. The use of the motor-generator equipment produces at once the bugbears of additional weight, low power/weight ratio and the heavy maintenance required on rotary machinery. With the 50 c/s traction motor, we have a heavy and complicated machine which has a poor starting performance, making it unsatisfactory for locomotive work at least, where it is necessary to operate at low speeds for long periods on freight work.

From a fixed-equipment point of view, this form of electrifica-

tion is very attractive. Anyone who has travelled on the Liverpool Street–Shenfield 1·5kV d.c. line and seen the massive structures required to support the ponderous conductor-wire system and its components will agree that it is desirable to use something much lighter and especially cheaper, if electrification is to proceed on a nationwide scale. This is so with this system, as the much higher voltage used implies very light traction currents and hence a lighter contact-wire system and supporting-structure system. The financial saving in steelwork and copper will be considerable. Similarly the higher voltage used produces great savings in substation costs as there are less of them, their equipment is very simple and there is no need for a railway-owned e.h.v. distribution system with its great capital cost.

The drawback to the use of such a high-voltage contact system, however, is the question of clearances. On this point, I must differ from the authors, who have tended to minimize the cost of obtaining clearances for 25kV a.c. The British loading-gauge is most restrictive, since in this country we were the railway pioneers. In any of the built-up areas, such as the approaches to London termini and in and around the Birmingham area, for example, the proliferation of over-bridges and tunnels of restricted clearance will make it very expensive to obtain clearances in these areas. A number of expedients have been considered to overcome this, such as a conductor rail at the locomotive-transformer secondary voltage, dead sections and a line voltage of 6·6kV in difficult areas. None of these are entirely satisfactory from an operating point of view.

Finally, I would stress that the main purpose and duty of British Railways is to keep the traffic moving freely and punctually. Electrification provides the ideal motive power to do this, with its ability for recovery after delays, the high power output easily obtainable and the important improvement, from a passenger point of view, of the lack of smoke or fumes. Obviously we all want railway electrification to spread rapidly, but the form used must have the virtue of simplicity and almost complete reliability. However technically interesting it may be to have new and exciting forms of power supply and such things as germanium rectifiers, if our electric locomotives and multiple-unit trains are to be, in effect, mobile laboratories with possible delays to traffic due to experimental failures, we cannot tolerate such a state of affairs. This is a point which is often forgotten by contractors and others outside the railway industry.

Mr. E. C. Rippon: I will confine my remarks to Section 3.4 of the paper.

It has always been tacitly assumed, when considering railway electrification at the standard frequency in this country, that the 132kV Grid lines would provide the primary supply to the a.c. traction substations. No doubt the authors have studied this aspect of the problem, and it would be interesting to have some details of the technical considerations which led them to adopt a primary supply voltage of 132kV.

The output of the traction substations is not given in the paper although it is obvious that this will be small in comparison with the outputs generally associated with 132kV bulk-supply points. Incidentally, would the authors in their reply give some estimated figures for substation outputs, both for heavy- and light-traffic-density projects? If the principles outlined in the schematic of Fig. 2 are implemented, i.e. the traction side is fed from substations containing a small number of 132kV transformers of moderate output, the substation costs will be very high. I cannot believe that the authors had in mind that the substations would take this form, and I would appreciate more information on this subject.

With reference to the transformers and the technical problems which arise, I am glad the authors propose to use the open-V connection. Even so, such transformers, which must be of the 'fully insulated' type, may be costly because of design complications necessary to ensure satisfactory surge and mechanical performance if the outputs required at 132kV are small. Again, the design of Scott-connected transformers for service at 132kV presents serious technical problems which will, in my opinion, outweigh any advantage they may have in providing a more balanced load on the 3-phase side. Another problem which merits some study arises from lightning surges being transferred from the 132kV lines—mainly by magnetic coupling between windings—to the traction side. Some form of surge protection will be necessary at each substation.

The authors' conclusion that the capital cost of a.c. substations will be less than d.c. ones may well be justified. I feel, however, that the paper contains insufficient information to make an assessment of the relative merits of the two systems, so far as substations are concerned.

Mr. R. A. Hore: In this country the traffic density is high, and it should be very much higher. Whilst the authors have made their case for the a.c. electrification of lines of low traffic density at the standard frequency, I am not sure that they have done so for those of high traffic density. Could the authors explain why the cost of the d.c. locomotive for 1·5 or 3kV is substantially the same as that of a 50c/s locomotive? The a.c. locomotive includes a transformer and rectifier equipment in addition to the equipment of the d.c. locomotive; and if dynamic braking is employed, as may well be desirable from the point of view of brake and tyre maintenance, a portion, at any rate, of the resistor and contactor equipment of the d.c. locomotive will also be required for the a.c. locomotive.

Even granted that the cost of the locomotives is the same, it seems that there are a number of factors which, for this country, favour d.c. electrification. There seems to be no definite advantage in being able to space the supply points as much as 50 miles apart unless the cost of the substations depends more upon their number than upon their rating; and whilst supplies for 50 miles of a.c. single-phase line would have to be from 132kV, I would have thought that supplies for the shorter length of d.c. line could well be taken, and taken more cheaply, from a lower-voltage system (bearing in mind the better phase balance, etc.).

Since electrification at 1·5kV d.c. by the third-rail system has existed in this country and given satisfactory service over a number of years, there would seem to be no objection to extending this or even adopting 3kV third-rail electrification. This should be considerably cheaper than a d.c. overhead system, particularly bearing in mind the alterations likely to be required for line-work clearances. As regards danger, 600 volts d.c. can be quite lethal, and since we have accepted this (and 1·5kV d.c.) for so long, there seems no logical objection to a 3kV d.c. system. As regards sidings, the danger position is different, but I do not consider that the electrification of sidings is an economical proposition in any case; Diesel locomotives seem to have their place there.

The authors imply that motors will continue to be nose-suspended. Surely the characteristics of this practice—bad riding, excessive track maintenance, poor adhesion, high weight, design restrictions on the motors and gearing, and heavy maintenance—should render this practice obsolete.

Mr. A. E. Bishop (*communicated*): One system that would appear worth investigating is 11kV unearthed with three rails, either catenary or ground supported. The line currents are the same as for a 19kV single-phase system, so that the 15–25kV range of the authors is covered. The advantages of the 3-phase 11kV system are lower insulation levels, no rail bonding, continuity of supply if there is a breakdown on one phase, lower line reactance, and balancing of the phases on the supply. The locomotives or motor coaches could use 11kV 3-phase induction

motors with pole changing and star/delta switches. The omission of mobile transformers and rectifiers should result in a considerable saving in capital and maintenance costs. The main difficulty appears to be 3-line current collection, which, at 11 kV, should not be too difficult. However, there is the overall advantage in operating at a standard voltage using well-established equipment.

Whatever system is used, I would add a plea for modern insulating materials operating at high temperatures in order to reduce size and weight. The use of these and high-permeability steels may well effect a considerable economy, even though the initial outlay may be greater.

Finally, the current rails seem very suitable for carrier-current signalling, and should enable the number of signal boxes to be considerably reduced with consequent greater safety and economy.

[The authors' reply to the above discussion will be found on page 431.]

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 19TH MARCH, 1956

Mr. T. E. Wilson: I do not consider that dual-system operation, as mentioned in Section 3.2, is to be desired. It will readily be appreciated that, if the pantograph of the locomotive has to operate over low-voltage overhead equipments, in addition to high-voltage a.c. equipments, it must be designed so that it is large enough for the heavier currents which must be expected at the lower voltage. This means that the pantograph must have heavier pressures to suit the lower-voltage line, and this will greatly affect the design of the high-voltage a.c. equipment.

The authors have referred to the ability to space feeding points long distances apart with high-voltage alternating current, but, in practice, the railway engineer always has to consider the switching requirements to meet the needs of the traffic operating department. The introduction of the extra switching stations means that the design engineer has to allow for variation of phase supplies to different parts of the line, with appropriate 'dead' sections between points not in phase. This consideration means that the suggested method of feeding the line, shown in Fig. 2, will hardly be applicable on main-line equipments.

One important advantage to be gained from the use of high-voltage a.c. equipment (referred to in Section 3.6) is that automatic tensioning can be used on much of the overhead-line equipment, whereas this is not readily usable on heavier, lower-voltage d.c. equipments.

The overall maintenance costs of high voltage a.c. equipment can, I feel, be expected to compare with, but not to improve much on, those of 1·5 kV d.c. equipment. Apart from the advantage resulting from the use of automatic tensioning, it has to be realized that a 25 kV single-phase overhead-line equipment requires greater clearances for work than a standard 33 kV 3-phase overhead power line. It will not be possible to undertake work on a 25 kV a.c. overhead-line equipment whilst it is live, as is done with 1·5 kV d.c. equipment. Further, the clearances from live equipment which must be allowed for work such as the painting of bridges or station awnings, signals, etc., have to be greater with 25 kV a.c. than with 1·5 kV d.c.

Mr. H. B. Calverley: The greater adhesion factor found by the S.N.C.F. for rectifier-type locomotives when compared with d.c. locomotives is perhaps not sufficiently stressed in the paper. The greatest possible mean accelerating tractive effort is obtained by having an infinitely variable control, as is possible on many convertor types of locomotive, equivalent to an infinite number of notches. However, this is not the reason for the large increase in adhesion factor claimed for rectifier locomotives.

The principal reasons for a higher adhesion factor are the parallel-connected motors and speed control by voltage, as opposed to series/parallel connections and speed control by resistance. The rectifier locomotive can then be accelerated at a tractive effort much closer to the basic adhesion limit, because, if a wheel should slip at a 'bad spot' on the rail there will be a greater tendency for it to stop spinning when it moves to a good rail, owing to the smaller rise in angular velocity of the slipping wheel with a steady voltage applied to the motor.

The S.N.C.F. findings mean that an 80-ton B_0–B_0 rectifier locomotive can exert nearly as much starting tractive effort as a 120-ton C_0–C_0 d.c. locomotive. If it is possible to build the required horse-power into the B_0–B_0 locomotive it seems reasonable for the railway engineer to prefer it. Only on a basis of comparison such as this can one accept the statement that rectifier locomotives should be no more costly than 3 kV d.c. types.

The authors dispose of the problems of the alternating harmonic currents and the negative-sequence current by the low-impedance-supply argument. But these currents, as wattless, flow in the supply system right back to the alternator and cause a certain amount of heating. Theoretically the cost of a.c. power to the railway should be greater for the 50 c/s system than for the d.c. system, since the wattless components reduce the ability of the plant to supply other customers.

Could the authors give an explanation of the reasoning behind the division of obstructions into two classes, so far as electrical clearances are concerned, i.e. those extending for short distances and those extending for some distance?

Mr. J. K. Lord: My only criticism of the use of such high-voltage contact systems is on the question of maintenance. Quite a large amount of maintenance is carried out between trains on the 1·5 kV d.c. overhead line while the line is live. With the higher alternating voltages, all overhead-line maintenance will have to be carried out under isolation conditions and I foresee that Sunday travel on British Railways will be no better in the future than it is at present.

Mr. H. Charnley: Whilst I agree that, in general, the rectifier-equipped rolling stock is probably best in this country as an interim measure, we must look further ahead. I am not advocating the use of a.c. motors for locomotive work, but I think their use may be considered for motor-coach work. The rectifier with its auxiliaries can be troublesome, and their use virtually precludes any regenerative features.

In the design of a locomotive extreme flexibility is not possible whichever type of equipment is used, but a convertor type is as flexible as any. For locomotives I think that eventually convertors will be used, and if these are of the a.c./d.c. type, I would suggest a low direct voltage, say 700 volts for a 700 h.p. motor, thus enabling an 8-pole design to be used which would give a lightweight motor.

The single-phase/3-phase convertor locomotive should be carefully examined, as the superior operating features can offset the extra cost and complication (high adhesion factor and automatic generation). Incidentally, a.c./d.c. convertors can also have automatic generation if they use separately excited motors, which are feasible and which will also give glue-like adhesion. We must not forget the power-factor correction these locomotives would give.

A great deal of detailed investigation work, which I carried out some years ago, exposed the fallacy that the convertor locomotive will have a poor power/weight ratio. The weight of the convertor set can be largely offset by saving on tractio[n]

motor weight. For instance, on the B_0–B_0 locomotive of the Manchester–Sheffield line, the four motors weigh 19 tons. For similar service on a convertor locomotive, the weight of the motors could be reduced to 9 tons, thus saving 10 tons here; in fact, the locomotive could weigh 74 tons.

Mr. K. F. Browne: Could the authors comment on an apparent discrepancy between the paper and the British Transport Commission's 1951 Report on Electrification?

If we consider only the 1·5 kV d.c. system, the Report states that the threshold of usefulness of electrification is expected to be of the order of 3 to 4 million trailing ton-miles per annum per single-track mile, whereas the authors mentioned 4 and 8 million ton-miles with 50 c/s electrification, with a rider to the effect that the figures would be higher if d.c. electrification were contemplated. Is this because the 1951 Report ignored the third alternative of Diesel running?

Mr. J. R. Sutton: I was a little perturbed to see that, in some cases, track bonds could be omitted altogether if earth conductivity were good. This seems to raise the possibility of the earth conductivity being poor on occasion, and whereas 1 or 2 kV would make little difference to a 25 kV locomotive it would make a great deal of difference to anyone touching the rail. Within what limits were the authors expecting to keep the rail-to-earth voltage?

Mr. F. Whyman also contributed to the discussion at Manchester.

[The authors' reply to the above discussion will be found on page 431].

RUGBY SUB-CENTRE, AT RUGBY, 20TH MARCH, 1956

Mr. W. G. Jowett: The standard practice for d.c. electrification is to feed the contact wire at the highest usable direct voltage in order to obtain the maximum economy in power-supply equipment, substation and overhead-line equipment. This limit, at present, is 3 kV and is dictated by the traction motor. For sound design and absence from flashover the limit is 1·5 kV per armature, and therefore, with 3 kV, two armatures must be connected in series. By preference and for maximum output, a voltage of 0·75–1 kV is desirable. The connection of armatures in series and coarse acceleration notching are necessary weaknesses with d.c. electrification which encourage wheel slip and therefore dictate that conventional d.c. locomotives are worked at a conservative adhesion factor. In spite of these limitations the d.c. traction motor has proved entirely satisfactory for traction service and superior to its a.c. rivals.

The rectifier-fed d.c. traction-motor scheme with transformer tap control permits smooth notching and parallel connection of traction motors (or equivalent), which allows higher adhesion factors to be used. At the same time it permits the traction-motor designer to select the most suitable voltage for service reliability and maximum output, and I endorse the authors' views that this arrangement provides the best all-round answer. An exception might arise where electric braking is the most important portion of the duty cycle. This is a special case, but it is conceivable that the economy of regenerative braking over rheostatic braking may warrant a different scheme.

As regards power supply, it is not always found that the traction load is a small portion of the supply capacity, especially in under-developed countries. Special arrangements in such cases may be necessary to deal with unbalance and harmonics, which must be a charge against the standard-frequency system.

With reference to line equipment, including substations, there can be no doubt that the a.c. schemes provide a simpler and cheaper solution.

Structural alterations for line-work clearance is a most difficult subject on which to generalize. The authors state that the number of sites requiring attention has more bearing on the cost than the clearance required. This is seemingly at variance with the British Railways' proposal to use 6·6 kV in congested areas and 25 kV on the open line. Such a major complication could hardly be justified if the authors' view is correct.

Telephone interference can be a simple matter to solve, or a prodigous burden, depending on who pays. In many highly developed countries the Post Office undertakes, as a normal improvement of the service, to bury the communication circuits. In under-developed countries the cost is charged to the electrification account, which may tend to retard the standard-frequency system.

I find it rather difficult to obtain a complete picture from Table 4. Total running costs are sufficiently similar to be accepted without further comment, but from the interest figures, it appears that the capital costs for 1·5 and 3 kV d.c. electrification are 57% and 24% higher, respectively than for standard-frequency a.c. electrification. Without a division of the capital costs, further comment is difficult, and I consider that this is the most important omission from the paper.

The authors state that rectifier locomotives should be no more expensive than 3 kV d.c. ones. I find that this is hardly true. If the choice is restricted to the straightforward bogie arrangements (i.e. B_0–B_0 or C_0–C_0) it is my experience that, where a.c. and d.c. locomotives of the same wheel arrangement are required for a service, the a.c. locomotive costs approximately 15% more than the d.c. one. Where an a.c. locomotive of simpler wheel arrangement than its d.c. counterpart can be used (owing to the improved adhesion possible with the a.c. locomotive) the costs of the two locomotives are about the same. This is based on British engineering practice, comparing simple d.c. locomotives with simple rectifier locomotives.

For 3-coach units the ratio of costs of a.c. (rectifier) to d.c. electrification is about 110–100% in favour of direct current, but if the increased adhesion permissible with alternating current is applied to compare 4-car a.c. units with 3-car d.c. units, the cost of a 12-car train is about the same.

Further, it must be borne in mind that a.c. equipment is substantially heavier than d.c. equipment, and therefore it sometimes happens that a concession on axle load is required before use can be made of the higher adhesion features.

It may be of general interest to compare, on a percentage basis, the results of a recent investigation:

	3 kV d.c.	25 kV a.c.
Cost of locomotives	104%	100%
Adding substations and overhead line these become	123%	100%
Adding power-supply equipment these become	120%	100%
Adding civil-engineering work these become	119%	100%
Adding communication equipment these become	104%	100%

This shows that it is dangerous to generalize, so far as costs are concerned, but there are possibilities of considerable economies with the standard-frequency system in certain cases.

Dr. J. C. Read: It appears that the permissible spacing between transformer substations will depend mainly on the voltage drop to the trains which is produced by the relatively high reactance of the overhead contact system, and therefore the allowable spacing will depend on the power factor of the current. It should be understood that the power factor that matters in

this respect is that of the fundamental component, i.e. cos ϕ, and not the total power factor (which includes the harmonics in the current). I believe that the low power factors quoted in the paper and elsewhere for rectifier trains are due to the use of the total power factor, which actually is irrelevant. With semi-conductor rectifiers on the trains, I think that the value of cos ϕ at the train will be about 0·95, and it is one of the advantages of the rectifier scheme that the substation spacing can therefore be somewhat larger than if 50 c/s traction motors were employed. This is particularly important with the arrangement proposed by the British Transport Commission, in which some sections of the line will be supplied at 6·6 kV and will therefore have high percentage reactance.

The permissible substation spacing is also affected by the value to which the voltage at the train can be allowed to fall. Direct-current series motors are not very sensitive to variations of voltage, but with ignitron equipments the limit is set by the ignitor firing circuit, whose operation becomes erratic below about 70% of the normal voltage. With semi-conductor rectifiers this limitation disappears, and the voltage at the train can be allowed to fall as low as is permitted by considerations of maintenance of the time-table.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. E. L. E. Wheatcroft and **H. H. C. Barton** (*in reply*):

Reply to the Discussion before The Institution

Most speakers have taken an optimistic view of the potentialities of standard-frequency electrification, but several have questioned whether the economic justification given in Table 4 is typical. These doubts have centred principally on telecommunication and on our insufficiently qualified statement that rectifier locomotives should be no more costly than 3 kV d.c. types.

In the first place we agree that each project must be decided on merit and that cases may arise when the balance tips in favour of direct current. For this reason, we tried to avoid stating categorically that the standard-frequency electrification will always prove cheaper, though we feel that in the majority of cases this will be so. Neither we nor the oversea railways with whom we have collaborated based our conclusions on 'paper studies'; indeed, many important factors—conductor clearance is one—were assessed accurately only after practical investigation. Our findings are based on oversea studies. Each of these studies presented different problems, and we had thought that few of these problems were strictly comparable with those in this country. The recent decision of the B.T.C. to equip major routes in this country for 50 c/s operation seems, however, to show that the advantages of this system may apply not only to high traffic densities but also where there is a considerable mileage in 'built-up' areas.

On the question of locomotive unit costs the manufacturers must, of course, have the last word. The discussion has emphasized that unit prices are an unreliable basis for comparison, and that the total cost of locomotives in the a.c. case may well be a little less than that in the d.c. case after reasonable allowance has been made for the better adhesive qualities of the a.c. locomotive.

With d.c. electrification open-wire telecommunication lines are permissible only if they are constructed and maintained to high standards and the separation distance is adequate. In the case given in the paper, the existing lines were too near the railway to be satisfactory with a 3 kV system. Even if this had not been so, it is doubtful whether the noise level, although probably within private service line standards, would have been acceptable to the Post Office for international trunk working. In each of the cases we studied, the Post Office engineers agreed with the proposals where their circuits were likely to be affected; indeed, they helped us to prepare the estimates. For various reasons we are becoming more inclined to the view that telecommunication difficulties tend to decrease. This belief has recently been strengthened by the decision of yet another oversea authority to follow trunk-road routes in preference to the railway on the grounds of easier access for maintenance.

Our estimates for telecommunication modifications were based on lead-sheathed armoured cables laid in the ground. Allowances were made for extra repeaters and the power supplies to these, as well as arranging for access to the control telephone pair to be available at mile intervals. Provision was made only for the essential railway circuits, which in this case involved some inter-district long-distance trunks as well as local circuits. No power distribution by cable was necessary in either the d.c. or the a.c. case, and over parts of the route, modern signalling was being installed separately. Not every railway signal engineer will agree to share a cable for vital circuits.

In the Belgian Congo, experience with 50 c/s electrification has shown that longitudinal induced voltages may be kept within safe limits by the use of screened cable buried near the track. We are doubtful whether carrying the cable on the overhead equipment, as mentioned by Mr. Harding, would result in a saving on high-voltage projects where the structures are of fairly light construction. Particularly is this so in the case of single-track routes, where structure locations may change from one side of the track to the other to simplify construction on curves.

The exchange-junction signalling difficulty, which Mr. Scantlebury mentions, while important in this country, has never been encountered by us oversea. It may be pertinent to mention in this connection that the West German railway administration now use tone-frequency signalling throughout its telephone system, the cables for which largely parallel their 16⅔ c/s electrification.

Our maintenance estimates included line equipment, substations, workshops, staff quarters and other buildings as well as rolling stock. In the 50 c/s case the rolling-stock component comprised about 40% of the total. These estimates were made in considerable detail with the help of the railway administration for whom we were working. As Mr. Manser suggests, the 50 c/s rolling-stock maintenance figure had to be deduced from experience obtained and freely given to us by other railways; indeed, his own department contributed no small measure of assistance in this matter.

We must wait until countries having both a.c. and d.c. systems have accumulated more experience before answering Mr. Warder's question regarding the comparative costs of line equipment maintenance. On present showing we think that the difference, if any, will be small.

We appreciate that transmission-line costs may militate against electrification in under-developed countries, but we have not met the special difficulty to which Mr. Whyman refers, because of the fact mentioned in the paper that the non-railway load requirements called for a sufficiently 'strong' transmission system.

With regard to the technical comments, we agree that rolling stock should be kept as simple as possible. Increased maintenance costs, as well as increases in the number of shopped vehicles under maintenance, must both be considered as factors militating against dual-system operation. On the projects whi

we have studied, dual equipped stock never had to be considered as an alternative to the high cost of alterations to ways and works. The average of £5 300 per mile on the latter account, which we mention in the paper, was fairly well distributed along the route. This would probably be a small sum compared with the cost per mile of the alterations involved in the installation of 25 kV conductors over the city railway routes in this country. We are indeed fully conscious of the technical objections to inter-running; all we postulate is that inter-running between one system employing current rail and another employing overhead conductors involves fewer unknown technical problems than inter-running between two systems which employ overhead conductors of different weights. The former case is susceptible to fairly easy economic solution if d.c.-motored rolling stock is used; the latter case may well present a crop of technical difficulty which will cloud the economic issue. We agree that it is a pity to spoil the good adhesion qualities of the a.c. locomotive by reverting to resistance control; however, economic considerations may take charge of this matter as, presumably, they did on the New York, New Haven and Hartford Railroad. We omitted to mention the varying voltage drop on each notch with d.c. control because good drivers allow for this, often subconsciously, to an extent that slipping is avoided.

M. Gastine has given information on the proposed further extension of 50 c/s electrification in N.E. France, and it is most significant to note that B_0–B_0 rectifier locomotives will be used almost exclusively on these new projects. The outcome of the studies which the S.N.C.F. are making with the lightweight 50 c/s traction motor for multiple-unit-stock applications will be followed with great interest.

Evidence in support of our statement that the 50 c/s traction motor is heavier than the $16\frac{2}{3}$ c/s motor is contained in Fig. 1, because these two machines are comparable. Reference 3 shows that, in 1951, a comparable d.c. machine was lighter although larger than a 50 c/s machine. However, the development progress announced by M. Gastine may well result in the 50 c/s machine being able to compete in size as well, when it will have wider application for use on multiple units.

As regards the cost of line work, Fig. 4, to be of value, had to be based on the factual experience of the single-track oversea projects which we have studied. It was based on a complete scheme with allowances for 'special work', although this was far less than would be the case in this country. Our estimates allowed for fully weatherproof equipment, and while not doubting the figures for the 400 route-mile project quoted by Mr. Cock, we are at loss to understand the difference between his figures and ours unless the climatic conditions permitted a cheaper form of construction. We agree that the cost per single-track mile for double-track construction would be more favourable to the d.c. case than is shown in the Figure. Automatic tensioning would add about 4% to the total cost of a.c. line-work.

Mr. Lane clearly agrees with our statement that the railway substations must be fed from a 'strong' point in a public supply system, e.g. by connection to the 132 kV side of Fig. A. These circuit-breakers are shown as conveniently shared. Presumably his arrangement is intended for duplicate supply all off one phase, rather than the 'open V', which, as shown in our Fig. 3, gives a double-ended feed to each section of the track.

We endorse Mr. Collis's remarks. The Pennsylvania Railroad, who have had over 6 years' continuous experience of this problem, have also found that the effect of the rectifier commutation ripple is considerably reduced at the line.

We consider that a line-voltage drop exceeding 20% is an unfair handicap to impose on main-line drivers who may be endeavouring to make up time with trains which have arrived, steam hauled and late, on to the electrified territory. Experience has shown that prolonged drops of even 20% produce operating-department complaints. We agree that it is technically possible to operate outside this limit; indeed, we have suggested that an occasional 50% drop should be permissible. The example which Mr. Whyman quotes, if this refers to the 12 suburban miles between Belleville and Cape Town, seems hardly a fair illustration of what will be generally acceptable to an operating department. We welcome the greater voltage range proposed for auxiliary machines.

We agree that economic justification, which can only be examined on present prices and future traffics, should not exert an overriding influence on electrification decisions. The imponderables which Mr. Inglis mentions, as well as passenger amenity, are rarely given the credit they deserve; they always result in an increase in the number of passenger miles per passenger.

Reply to the Discussions before the North-Eastern Centre, the North-Western Utilization Group and the Rugby Sub-Centre

The London discussion and our reply to this covers many of the matters raised in the discussions at Newcastle, Manchester and Rugby. We propose, therefore, to confine the following remarks to the new points which have been raised. In doing this we think it helpful to mention that, in the month separating the Newcastle and Manchester meetings, the British Transport Commission published details of their plan to adopt the standard-frequency system for extensive railway electrification on the London Midland, Eastern, North-Eastern and Scottish Regions of British Railways. This fact tended to emphasize comparisons between conditions in this country and those oversea.

The major differences are those of power supply and load, and ways and works modifications. In reply to Mr. Rippon, the traffic density would, at the most, require the 25 kV substations to be rated for 4 MVA peaks, and their smaller number—four instead of about fifteen with a 3 kV d.c. system over a 150-mile route—would result in substantial saving. We agree with Mr. Jowitt that, in under-developed countries, it is likely that the railway load will be greater in comparison with the industrial and domestic load, and, in consequence, the out-of-balance and the harmonics of the former may require the provision of special equipment. But as a counterbalance to this special equipment, the cost of civil-engineering works necessary to obtain satisfactory clearances for oversea 25 kV operation will, as emphasized by Mr. Davidson, be much less than in this country. Our statement that the number of sites requiring modification had a greater bearing on the cost than the amount of work required at each site was not intended to apply to British conditions. The two clearance ranges to which Mr. Calverley refers were quoted in Table 3 as French practice, on the limited experience available at the time the paper was prepared; we understand that they arose from the difficult tunnel sections on the Savoy line.

Messrs. Hore, Calverley, Charnley and Jowitt have all raised questions about rolling stock. We agree that the axle-hung motor has disadvantages, although we are not convinced, on balance, that other suspension methods will eliminate all the objections raised by Mr. Hore without introducing new ones. We cannot agree with Mr. Charnley that the saving in motor weight will offset the added weight of the motor-generator set and the extra constructional weight necessary to support it on the frame of a convertor type of locomotive. We should give consideration to regeneration only if a basic load is available at all times to absorb the regenerated energy.

Objection is raised in this country to current-rail systems for locomotive applications because of the rail gaps which are unavoidable at junctions. We do not, however, entirely support

this objection. The New York, New Haven and Hartford Railroad successfully operate their locomotive-hauled trains over the New York Central current-rail system.

With regard to line-work construction, the question of automatic tensioning is by no means clear-cut, because complication, cost, temperature range and train speeds all have a bearing on this matter. We agree with Messrs. Wilson and Lord that the maintenance procedure for 25 kV will be different from that for 1·5 kV d.c. However, such a procedure is quite practicable as has been proved by several Continental railways, which, in addition, seem to have solved the problem of high-speed light-current collection.

We do not consider that rail potentials will ever reach the values suggested by Mr. Sutton, irrespective of whether the rails are bonded or not. Indeed, we are of the opinion that, on an a.c. scheme, the voltage drop at the train would become intolerable long before the rail potentials exceeded those values usual on d.c. schemes, and the system would be designed to avoid this.

In reply to Mr. Browne, we have always felt that the B.T.C. 1951 Report (p. 68) 'left the door open' to standard-frequency electrification. Our economic comparisons were made with Diesel alternatives on oversea projects, whereas the B.T.C. Report compared electrification with steam on the home railways at a time when copper was cheaper than it is at present.

Our experience is at variance with that of Mr. Jowitt on the significance of the telecommunication costs, for the reasons already explained in our reply to the London discussion. If Table 4 is read in conjunction with Fig. 4 we think that Mr. Jowitt's difficulty in forming a picture of the capital costs will be largely resolved. We are glad to have his confirmation that it is unwise to generalize, and we note the figures which he puts forward in support of this.

We are interested in Dr. Read's remarks, particularly in regard to the better regulation with rectifiers as compared with 50 c/s traction motors. We agree that voltage drop may become a significant factor in a 6·6 kV electrification; this is also a matter to be taken into account in oversea work in cases where transmission systems are liable to be 'weak'.

DISCUSSION ON

'SERVICE EXPERIENCE OF THE EFFECT OF CORROSION ON STEEL-CORED ALUMINIUM OVERHEAD-LINE CONDUCTORS'*

Mr. H. R. Bhatia (*India: communicated*): We have had two instances of conductor breakage on the 132 kV trunk transmission line of the Punjab Power Grid. The conductor size is a.c.s.r. 0·125 in^2 equivalent copper section (aluminium, 30/·093 in; steel, 7/·093 in). The particulars of the two failures are given below:

	No. 1	No. 2
Date	23.7.55	18.8.55
Time	20.05 hours	9.06 hours
Circuit No. ..	2	1
Conductor	Bottom	Bottom
Location	100 ft from suspension tower	120 ft from strain tower
Distance from compression joint	2 ft	8 ft
Condition of joint ..	Not satisfactory (aluminium strands not properly gripped)	Very sound

Both these failures occurred in the same span, and only one circuit was in commission at the time of failure on each occasion, the other being under permit. The breakage occurred on the loaded conductor. The fact that failure occurred near a compression joint in each case indicates that corrosion had started near the end of the conductor before it was strung and penetrated to some distance during service. The line has been in service for about 23 years. The failure occurred in a rural locality, far away from any industrial town. Since the failure occurred at a fair distance from the strain or suspension point, it was obviously not due to mechanical over-stressing of the conductor. If the authors could give their views on these failures, these may be helpful in obviating future failures.

Dr. J. S. Forrest and **Mr. J. M. Ward** (*in reply*): Mr. Bhatia does not say if the conductors were in fact seriously corroded; unless the conductors were in very bad condition we should attribute both failures to poor contact between the aluminium strands and the sleeve of the compression joint. Even a relatively slight increase in contact resistance causes a large fraction of the current to transfer to the steel core, which then fails owing to overheating under heavy load or short-circuit currents. The fracture commonly occurs within a few feet of the mouth of the compression joint. In order to prevent such failures as far as possible, the aluminium strands should be thoroughly cleaned before compression and the joint filled with grease.

* FORREST, J. S., and WARD, J. M.: Paper No. 1611 S, January, 1954 (see 101, Part II, p. 271).

DISCUSSION ON

'SAFETY IN THE USE OF PORTABLE AND TRANSPORTABLE ELECTRICAL EQUIPMENT IN INDUSTRY'*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 3RD MAY, 1954

Mr. G. S. Buckingham: The supply industry does not generally like it to be thought that electricity is dangerous, but it is realized that there are dangers and that certain precautions must be taken to overcome them. One of the points I have looked for in the paper is some suggestion that an extra factor of safety can be obtained by taking such precautions as providing equipment with insulated handles designed so that an operator does not maintain a full and tight grip but can release them easily. In domestic premises where earth connections are not very good, we use a large number of earth-leakage trips. They are not perhaps so complicated or so expensive as the equipment described by the author, but they have proved to be extremely reliable, and are offered to the domestic consumer as his safeguard.

The author refers to American practice, where a great deal of distribution is at 110 volts, but he does not give any statistics of comparable accidents which occur in America. I do not know whether he has any such information, but I think this might be most useful evidence of the value of his decision to use 110 volts for factory distribution systems. Will the author comment on the selection of fuses for the protection of 110-volt systems?

Mr. E. Coleman: I should like to describe what I think may be an improvement to the unit shown in Fig. 10. It entails the following modifications:

(*a*) Addition of an 'off' button to break the monitoring circuit.
(*b*) Arrangement of the earth-leakage circuit-breaker so that it can be closed, but not opened, manually.
(*c*) Addition of an isolating switch for emergency use, arranged so that it can only be reclosed by an 'authorized person'.
(*d*) Omission of the existing test button, but the tripping resistor to be inserted between phase and 'relay-open' contact.

With this arrangement, safety would be enhanced because complete and regular testing of the effectiveness and sensitivity of all the vital parts (the monitoring leads, the relay and its contacts, the tripping coil and its earth connection) could not be neglected. A further improvement would be to interlock the socket-outlet to prevent plug withdrawal if the circuit-breaker failed to trip; controlled maintenance working would thus be more assured.

The importance of proper maintenance of all equipment, and protective devices in particular, cannot be too highly emphasized. The 1951 Electrical Accidents report refers to a fatality due to a fault on a machine 'protected' by an earth-leakage circuit-breaker. Investigation, the report continues, disclosed the fact that five out of seven of these circuit-breakers on the same premises failed to respond to test. This suggests a deplorable lack of proper maintenance, and I regret that instead of stressing this point the writer considers it wiser to advocate the addition of differential-current protection. The important point is that all methods of protection are almost certain to become useless unless the necessity of good maintenance is recognized.

Unfortunately the Factory Regulations do not help us much in this respect. Until it is a statutory requirement for all installations to be the responsibility of a properly defined 'authorized person', we cannot even begin to expect efficient maintenance everywhere. So long as such responsibility may legally be delegated to anybody, much of the effort directed towards evolving Wiring Regulations, etc., will be lost.

Mr. R. A. Joseph: It is to the author's credit that he draws attention to the difference between portable and transportable equipment. I agree that 50-volt supplies should be utilized wherever possible, but loading on many items makes this virtually impracticable. Whilst a 50-volt plug installation could be planned for an individual factory, the difficulties facing contractors are considerable.

The monitored earth circuit-breaking unit shown in Fig. 10 is a useful solution to the problem for transportable equipment. If a fault has developed on the winding of the apparatus since it was last used (e.g. as a result of rough handling), the circuit-breaker will be closed on to a fault and will not trip out again until first relay B, and then the main circuit-breaker, has operated. Will this time-delay permit a dangerous voltage rise to occur on the case of the transportable apparatus?

I also note that relay B is not checked by the test button. Would it not have been more satisfactory to connect the test button between a line and the connection from the pin of the outgoing socket which is connected to the pilot earth core? The test would then be applied to relay B and to the main circuit-breaker, instead of to the main circuit-breaker only.

Mr. A. J. Mare: Mention is made of the true earth-leakage-protection circuit-breaker advocated by Mr. T. C. Gilbert. In one case this voltage-operated equipment was installed, by request, in a situation as a main circuit-breaker where there were overhead lines. There was very good earth in the form of pipework all around the site, and no portable equipment, hence it was never called upon to do any work and was a complete waste of money. In another case the same form of protection was applied to a trailing cable in a gravel pit, feeding an excavator, and here, when the excavator caterpillars ran over the trailing cable, cutting and short-circuiting all cords, the relay coil burnt out.

The author carried out life tests of applying 240 volts to the low-voltage trip coil and experienced 5% burn-outs of coils. This, he states, he has now overcome by an early-making auxiliary contact. Since the above experience I have used core-balance earth-leakage protection, complying with Quarries General Regulations, and I was hoping that the author would not have dealt so lightly with this type of protection.

As the author is aware, there is still a further type of protection used in coal mines, namely a current transformer in the neutral-to-earth lead on the trans-switch unit, and an earth-fault current returning to the star point of the transformer operates a trip on the feeding circuit-breaker. Both the latter methods are very robust and have had Home Office approval for a long time. It would be interesting to know whether there are any official accident figures showing the relative number of accidents, or fatalities, on core balance and current transformers in neutral systems, as compared with voltage-type earth-leakage protection.

* BUNTING, J. W.: Paper No. 1648 U, April, 1954 (see 101, Part II, p. 583).

It is apparent that the majority of portable and transportable appliances to be found in a works will be controlled by a 30 amp or 60 amp triple-pole circuit-breaker, which would probably have a rupturing capacity of 5 MVA, and are presumably installed where the fault current does not exceed this figure. However, the cost of this device will rise very considerably if the fault condition is approximate to 25 MVA.

Does the author have his multicore cable and plug directly interlocked with the circuit-breaker, or does he have to use the more normal interlocked switch-plug in addition?

Mr. E. P. Tomblin: The Senior Electrical Inspector's Annual Reports indicate that for several years approximately one-third of all accidents in this country have been associated with portable apparatus. The risks of electric shock in these cases remain unchanged, but a disturbing feature over the past 15 years has been the steady increase in burn injuries due to arcing when faults occur on portable equipment and flexible cables.

This is due to increased fault energy available from medium-voltage networks nowadays, and the author might have made reference to this hazard when dealing with the importance of protective equipment. The severity of burn injuries in these cases appears to be directly related to the size and type of fusegear in circuit with the portable apparatus involved in the accident.

The author's remarks under Section 5.2.2 of the paper are likely to involve someone in a breach of the law. He states that a 50-volt supply with a maximum of 25 volts to earth is sufficiently safe without earthing of the frame of the portable equipment. Electricity Regulation 13 indicates that such an arrangement is permissible on d.c. circuits, but clearly states that with alternating currents the metallic casings of portable apparatus must be efficiently connected to earth whatever the system voltage. I have had this interpretation of the Regulation confirmed by one of H.M. Electrical Inspectors.

The overall advantages of a 110-volt system with mid-point earthing have been clearly brought out by the author. Such a system has been adopted by the Central Electricity Authority for use in generating stations, and in addition, electricity supplies at this voltage are made available to contractors on all new building sites and it constitutes one of the terms of contract.

The paper does not emphasize sufficiently the troubles experienced with portable tools operating at 50 and 25 volts owing to excessive voltage drop, poor regulation, etc., and in my opinion the use of these extra low voltages, particularly in large premises, is pushing safety beyond reasonable limits. The poor performance of 50-volt rotary tools under conditions of severe voltage drop usually results in the operator dispensing with the equipment and obtaining a 240-volt tool from somewhere.

In his conclusions the author assumes that the electrical installation comes under the control of the user of the portable apparatus. Consideration should be given to private contractors and Electricity Boards who have to send their employees to do work on other people's premises and are faced with supply voltages varying between low and high and earthing resistances possessing similar characteristics. Electricity Board engineers have given careful consideration to this matter, and opinion seems to be in favour of 110-volt tools and portable transformers having earth-leakage protection on the lines developed by Mr. Butcher.

The author emphasizes the importance of continuity of the earth conductor, but does not make reference to the shortcomings of routine test methods in common use. It is not enough to check continuity of earth conductors by means of battery-operated continuity testers. Experience shows that the strands of these conductors tend to break at the point where maximum flexing of the cables occurs. Should an earth fault develop under these conditions there is every possibility that th remaining strands of the earth conductor will melt before th protective fuse and earth continuity is lost. Heavy-curren testing of the order of 30 amp will break down a defective eart conductor of this type and indicate that a replacement i necessary.

Mr. F. E. Butcher: I should like to begin with a comment o the biological or physiological aspect, because it is possible tha the author has additional information. There was some indica tion in connection with work being done some years ago, whic was never finished, that the term 'body impedance' should b used rather than 'body resistance', because it was then show that at low voltages the equivalent circuit of a body was capacitance, a resistance and another capacitance all in serie One capacitance was the in-going point and the other capacitanc the out-going point. Their values, of course, depended amo other things on the area of contact with the electrode—whic might be the casing of a portable tool. I believe the resistanc was non-linear. The curve which the author showed seemed t confirm this non-linearity.

On the question of fusing on low voltage, there is a doubl characteristic fuse, one part being a thermal delay and the othe being the normal h.r.c. type.

I was interested in the absence of any mention in the pape of provision against a short-circuit in the monitoring circuit i the cables of portable or transportable equipment. A meta wheel could cut the cable, short-circuiting the monitori circuit and leaving the equipment frame alive. Has the autho any experience of the circuit which monitors resistance up an down instead of just for a high value?

The economics of a unit for every outlet point as agains distribution scheme with a central unit should be studied in eac case. With a large installation the former does not enab advantage to be taken of the low load-factor of portable tool

With the circuits in general use in this country we must rel on high fault currents unless some other method of protectio is introduced. This is inherent and is, of course, the reason fo the high current causing the splashes and burns which have bee mentioned.

Any system which will enable the current to be reduced shou be of considerable help. Has the author any experience o monitoring using h.f. currents?

Interesting experiments were conducted under extreme cond tions with the circuit shown in Fig. 6 using transportable equi ment standing on a foundry floor—metal-laden sand. A earth wires in the flexible cable were disconnected and fu voltage faults applied to the appliance casing.

Clearance of the faults occurred without appreciable shoc to a man standing on the floor and holding the casing.

Mr. A. R. Wade: Could an indication be given of the gener standard of maintenance in the factories where the acciden described in Sections 2.2 and 2.3 occurred?

The industry seems to have difficulty in producing a we designed plug top for industrial use with adequate phase shiel and cable grip to B.S. 546 or B.S. 1363. I should like to ha the author's comments on this.

I should also like to know whether he would recomme plugs and sockets conforming to B.S. 1363 for industrial us and to hear of his experience with earth-loop testers—par cularly those passing a substantial current through the neutr line and earth path.

Mr. K. P. Koh: The author's estimation of voltage drops cables for 110-volt 50 c/s supply is incorrect. According Table 5 of The Institution's Wiring Regulations, 1950 editio a 7/·029 in cable gives a drop of 1 volt for every 17 ft of 'leng of run' when carrying 15 amp. Therefore the 120 yd ring ma

described under Section 5.3.1.3 paragraph (*a*) loaded at the far end with 2 kVA would have a voltage drop of approximately 6·4 volts—not 4 volts. Similar errors are to be found in paragraph (*c*).

The alternative to protecting a transportable equipment with a circuit-breaker is a fuse, which gives uncertain protection against faults to earth for ratings approaching 75 amp on a 240-volt system. This means that for outputs approaching 18 kVA and above, fuse protection is not an alternative to circuit-breakers. It is therefore good practice to install circuit-breakers for the protection of all transportable equipment as recommended by the author.

The reason for the author's recommendation that earthing of apparatus on 25-volt supply be dispensed with could be misunderstood and carried a stage further by omitting the earthing of the centre tap of the 25-volt winding of the transformer. This would expose the winding to switching surges leading ultimately to the appearance of 430 volts on the portable apparatus used.

Messrs. W. A. Vivian and **R. Paterson** also contributed to the discussion at Birmingham.

[The author's reply to the above discussion will be found on page 447.]

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 12TH OCTOBER, 1954

Mr. S. R. Mellonie: The author has made a useful contribution to the search for safety in the use of portable electrical devices. It would appear, however, that undue emphasis has been placed upon the danger in the use of such devices. There are in this country at the present time about 14½ million consumers, which indicates at least 30 million users of portable apparatus in the form of tools, fires, kettles, etc. The statistics show that the number of fatal accidents on the domestic side is of the order of 40 per annum, indicating roughly one per million users. It is suggested that this is a true indication of the risks involved in the normal use of portable appliances, although it must be admitted that special conditions exist in such cases as work inside boiler shells.

The author shows that a very high degree of protection can be obtained by the use of a supervised or monitored earth lead incorporating devices which fail to safety. This naturally leads to a rather complicated control unit which may in itself be a source of failure.

Reference is made in the paper, in Sections 5.2.2.1 and 5.3.2.2, to particular faults in which the earth wire becomes detached and makes contact with the live metal. This, however, would seem to indicate either bad workmanship or bad design which could readily be rectified. In any case it would be reasonable to expect that such an accidental connection would result in the operation of the fuse controlling the circuit, as such contacts would normally amount to a short-circuit. In this respect it would be as well to place on record that in those areas where a factory is supplied via a metal-sheathed underground cable, and the metal sheath is used as an earth conductor, the impedance of that section of the earth loop represented by the underground cable is of the order of 0·5 ohm. Hence, an effective earthing system on the consumer's premises should result in passing sufficient current to cause a 30 or 60 amp fuse to operate in less than 0·03 sec, i.e. 1½ cycles.

The recent improvement in the mechanical characteristics of plastics based on woven glass suggests that such a covering could be applied to the whole of the body and handle of a typical small portable drill which could then be supplied from a 240-volt circuit. This would be a very simple and probably cheaper solution than the ingenious arrangements shown in the author's Fig. 9.

The author rightly emphasizes the important part that maintenance plays in the avoidance of accidents. The frequency of examination should vary with the nature of the work on which portable tools are used. The period may vary from seven days to six months, depending on working conditions.

Mr. W. E. G. Robinson: In Section 5.2.2.1 it is pointed out that there are considerable dangers in using portable transformers fed by 240-volt flexible leads, but on most installations it was economically impossible, especially on large works, to install fixed low-voltage transformers or ring-main systems, and therefore in a lot of places the use of portable transformers will be not only a temporary expedient but probably a permanent one, especially since, in many instances, these portable tools might have to be used outside the works in question in other people's factories; surely it is best to get the voltage of the portable tools down to 110 volts, taking note of the difficulties that can arise from the use of portable transformers—which I think are somewhat over-emphasized.

Mr. D. A. Picken: In Section 3.1(*a*) the author says that a current as low as 15 mA may cause muscular contraction. This figure of approximately 15 mA was found by Dalziel as a result of a considerable number of experiments on students at California University. Carrying out similar experiments on a wide variety of people in this country not only suggests that the average for normal people unaccustomed to electric shock is somewhat lower than this mean figure, but further, a considerable proportion of people cannot maintain muscular control when subjected to the passage of currents as low as 7 or 8 mA.

The figures given in Section 3.1(*b*) are not in accordance with more recent experimental data. The minimum time during which the muscle can respond to electrical stimulation is of the order of 10 millisec, whilst the heart beats once per second, and only a proportion of that period is susceptible to inducing fibrillation. If a shock occurs during that period of adequate current density, then fibrillation will ensue.

In order to be sure of stimulating fibrillation one may have to persist with the shock over the whole heart-cycle, but this does not mean that a shock cannot occur in less than one heart cycle. Incidentally, the minimum value of 100 mA is subject to doubt. Other authorities who have carried out considerable experiments on isolated and animal hearts suggest much lower figures—possibly as low as 25 mA.

Higher currents, on the other hand, possibly upwards of 300 mA, are not likely to cause fibrillation since they induce a state of complete tetany in the muscular system of the heart which is much easier to deal with than fibrillation.

To sum up, fibrillation may occur with very short shocks, possibly of the order of 1/40 sec, with current in the range 25–300 mA passing through the body. Above this figure, if the path of the shock is directly through the thorax, fibrillation is less likely to occur.

Treatment of Fibrillation. The author infers that it is not possible to treat fibrillation. A number of treatments are available including injection of acetyl-cholin, counter-shock treatment; and probably protracted use of some artificial respiratory method, such as the Eve rocking stretcher, which both oxygenates the blood and circulates it; for Jellinek, among others, says that fibrillation is reversible provided the cerebral centres can be protected from collapse.

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There are, however, other causes of death by electric shock due to nerve blocks which can be caused by excessive stimulation of the nervous system due to small currents. These are possibly as common a cause of death as fibrillation.

In Section 3.2 it is suggested that 1 000 ohms is a normal value for the effective resistance of the body, and whilst this might be a mean figure, or even a little low for the mean figure, it is by no means a minimum figure. I would therefore suggest that something of the order of 400 ohms is possible. Incidentally, the Americans use the figure of 500 ohms in their safety practice.

Kervran's information on the variation of resistance of the body related to the voltage applied is important, and it does greatly minimize the liability to electric shock due to reduced voltage. Mr. A. H. O. W. de Bats, the Senior Electrical Inspector of the Dutch Factory Inspectorate, has collected data comparing the liability to fatal electric shock as between a 220-volt system and a 119-volt system. Statistics covering a period of some 20 years—after careful analysis and elimination of all factors not common to both systems—suggest that the likelihood of fatal shock occurring on a 220-volt system is 6·7 times as great as that on a 119-volt system.

Other factors which I have suggest that the ratio between 110-volt and 55-volt is of the order of 6 or 8, and that this will result in a liability to death, taking 230-volt as 100%, of only 2%, and this will not be greatly reduced until the voltage is as low as 5·20 volts; for, whilst 'classical' electric shock (i.e. where death occurs directly owing to disturbance of the normal nervous control system of the body) is unlikely at 55 volts, a passage of a much smaller resultant current may cause death either by disturbing the balance and causing a man to fall, or, alternatively, by inducing fear. The latter effects will persist so long as the current can be felt, and taking the minimum current which can be felt as something less than 1 mA, 5–20 volts can be felt by a considerable proportion of people and may therefore cause death, although not through electrocution.

From this, I would suggest that to achieve absolute safety some voltages less than 12 volts must be used, and the difference in liability to fatalities between a 55-volt system and a 25-volt system is slight and does not justify any relaxation of the precautions. I think that a 110-volt system lends itself to better safe working methods than does a 50-volt mid-point-earthed system, and even given the same standards of precautions there would be a negligible difference in liability to shock, so I agree that for portable tools 110-volt supplies are probably the most practicable way of achieving maximum safety. In any case, the use of portable transformers without elaborate precautions introduces, in only slightly lesser degree, the hazard of normal-voltage portable apparatus.

The author says of the 50-volt system that it is safe enough to be used without earthing. As I have previously said, the safety is negligibly greater than that of the 110-volt mid-point-earthed system, but the safety may well justify not earthing the equipment provided that it is to be used at ground level where a fall is not a hazard.

Mr. J. W. Binns: There are people who consider that certain medium-size and small personal tools such as drills, etc., which may be used under arduous constructional conditions, constitute the main danger if operated at mains voltages, and it is considered worth while to go to extra low voltages for these and thus obtain something approaching 100% safety in their use.

The factories with which I am at present associated have adopted the extra-low voltage or 50-volt centre-point-earthed system. Whilst, as the author has pointed out, there are difficulties with 50-volt installations and equipment, I do not think he has indicated the possible savings in maintenance costs which can be obtained. Owing to general freedom from troubles with this extra-low-voltage equipment, and because of its greate inherent safety, periodic examinations and tests can be materiall reduced.

In our particular circumstances we have the need on occasio to use portable equipment within special protective cabinet handled by suitable glove equipment. Such tools can b affected by radioactivity, and consequently cannot be very easil maintained. Extra-low-voltage equipment in these circum stances answers the requirement very well indeed.

My experience in this field has shown that the followin should receive attention:

(*a*) It is essential that standard schedules of plugs and sockets fo various voltages be made for a new installation to ensure adequat safety.

(*b*) Portable equipment should be carefully inspected, tested an maintained, and rigid discipline observed in the use of the syste when formulated.

(i) The provision of centres for the reception of portab equipment and controlling its issue is also a help to ensure it maintained in good condition.

(ii) Tools used on construction projects and on more arduou duty should receive more frequent inspection and test.

(iii) In all cases careful record should be kept.

(iv) Tests on earth connections to portable equipment shoul be made by the passage of current sufficient to operate the appro priate protective device.

(*c*) I heartily agree that adequate earth bonding is necessary on a permanent installations, and periodic tests of such earthing an bonding should be carried out.

(*d*) In general, I prefer fixed transformer units, but for factori during change-over to low-voltage working a limited number c portable units, preferably fitted with an earth-proving devic should be used.

Mr. G. S. Light: I cannot agree that battery-operated equip ment is inherently safe, as stated in Section 1.3. After all, motor-car ignition system is battery operated. Presumably fatal shock is obtainable from a 120-volt h.t. battery. On battery photographic equipment used in thousands incorporate a 30μF capacitor charged to 2·5 kV, which is undeniably letha

Throughout the paper no account is taken of equipment i which the mains voltage is stepped up. For example, Geiger Müller counter tubes operated at about 1 kV are not made safe by lowering the mains voltage, since the 1 kV still has to b obtained by step-up and rectification regardless of the suppl voltage. Admittedly the current obtainable from the averag Geiger supply may not be lethal, but often there is a larg capacitor charged to 400 volts in the associated counting equip ment, and through internal faults this lethal capacitor coul discharge through the body if the voltage should appear betwee the instrument case and the probe case.

I cannot understand why, in Section 4.3, it should be difficu to prevent the neutral becoming earthed, or to know when th occurs. The insulation and fusing requirements of the phase are known, so what stops one applying this technique to th neutral if required?

To the principles enumerated in Section 5.1 there should surel be added the proviso that lethal voltages should not be accessib to a standard finger (see B.S. 415: 1941).

In Section 5.2.1, I should have liked to see it stated that th transformer should have an earthed interwinding screen.

The second paragraph of Section 5.2.2 is incomplete withou the condition that all supposedly earthed metalwork such a handrails, ladders, platforms cannot become live. If th happens a man touching it or standing on it can be electrocute from the earthed casing of his portable tool. This is not fanciful —it has actually occurred.

The earth-monitoring system in Figs. 9 and 10 provides pro tection which is not as complete as it seems. If (*a*) the pilo

earth short-circuits to main earth in the cable or plug, (*b*) both earths become disconnected at the transportable equipment, and (*c*) phase goes down to case in the equipment, there is then a lethal situation in which the circuit-breaker is still on. Admittedly this requires the coincidence of three conditions, but most electrocutions *do* occur through the coincidence of two or more faults. A suggested way to decrease by several orders of magnitude the probability of danger, without adding significantly to cost, would be to take pilot earth to transportable case through say 500 ohms, and to use a relay at B which remains closed only when its exciting current is within both upper and lower limits. For the circuit-breaker not to trip on a fault we must then make condition (*a*) above, that 'the pilot earth acquires fortuitously an earth leakage of the right value', which is practically inconceivable.

Mr. H. Cahm: The usual practice of the Electricity Authority's North West Merseyside and North Wales Division with regard to the voltages in use for portable tools and hand-lamp lighting on construction sites and in new power stations may be of interest. Shortly after vesting day it was found that a variety of voltages were in use, particularly in places such as construction sites, where dangerous situations could exist. For a period of two years it was agreed to allow existing arrangements to continue, but new installations would have to conform with certain safety requirements for this kind of apparatus.

The voltages decided upon were 110 volts single-phase with centre point earthed, for portable tools, and 25 volts with centre point earthed, for hand-lamp lighting. These are now in general use.

On construction sites the 110-volt supply is derived from step-down transformers located at suitable spots. A large-capacity portable—or rather transportable—transformer with a ratio of 415/110 volts single-phase and a capacity of 25 kVA has been frequently used. These transformers have a set of enclosed air-insulated busbars on the 110-volt side, from which substantial connections can be taken through fused plugs and socket-outlets.

For fixed permanent installations it is a matter of economics to decide either on a low-voltage ring main with socket-outlets or a number of radial feeders with step-down transformers having multi-way socket-outlets on the 110-volt and 25-volt windings.

Originally it had been intended at certain stations to rely mainly on compressed-air tools, but many of the positions where tools are required are so far from the compressor that this system has had to be reinforced by electrically-operated tools. With the 25-volt lighting supply a high-output lamp taking 300 watts has been found very useful.

A point that has not been mentioned by previous speakers is that the length of trailing lead from the supply point to the tool or lamp should be kept down to a few feet, since long leads which may trail around steelwork columns and masses of pipework can lead to danger.

Mr. F. H. Merrill: In our organization we have adopted a 50-volt mid-point-earthed system for both hand-lamps and portable tools. We discourage the use of portable electric tools as much as possible, since we feel that air-operated ones are safer and more robust. We do not use any portable transformers. The author is at great pains to show that the 50-volt system has grave disadvantages for portable tools, and quotes figures which prove that prohibitively large cables are necessary to feed them if the voltage at the tool is to be maintained at 95% of the rated voltage. In practice this bogey is not as serious as he states. A 1 in drill will require its full power only for short periods, and in any case I would be prepared to tolerate 10% or even 15% voltage drop when it does. For these reasons I would also be quite prepared to use a 15 amp outlet for such a duty.

The author, in his recommendations, states that hand-lamps should be fed from a 25-volt mid-point-earthed system, presumably with portable transformers, a system which has all the disadvantages from the safety point of view which he quotes against the 50-volt system in Section 5.2.2.1. If fixed transformers were used a very extensive installation would be required. A 50-volt system, which is perfectly safe, can be provided for only marginally greater expenditure on transformers and primary wiring, and will serve both for hand-lamps and for portable tools. We find that for every portable tool, we have 20–30 hand-lamps.

After our experience with a very extensive 50-volt system in two works occupying 300 acres, we are more than ever confident that our choice of the 50-volt system was a correct one.

With regard to transportable equipment, I feel that too much emphasis can be placed on earth-leakage protection. Earth-leakage protective devices were originally developed for situations where it was difficult to obtain a good earth. In our experience this is never a difficulty in a chemical works and the main problem is to ensure that the earth lead from a socket to a piece of transportable plant is in good order. Surely all that is required is a simple circulating-current pilot-wire system which will cut off the power to the appliance if there is a failure of the earth core or the pilot wire.

[The author's reply to the above discussion will be found on page 447.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 8TH NOVEMBER, 1954

Mr. F. Murgatroyd: As H.M. Electrical Inspector of Factories, I give general support to the proposals which are contained in the paper. My Department and the author are 'speaking the same language' on this subject, and I agree that with a fixed installation at 110 volts a.c. and its centre-tapping earthed, a high degree of electrical safety is secured. A recent shock fatality in this area, due to bad wiring on a non-earthed 650-volt 3-phase transportable brick conveyor, has indicated again the importance of voltage reduction and (as in this instance) the additional protection available by the use of the devices and circuits illustrated in the paper. I stress 'additional protection' because the law still requires solid earthing, a fault path of low impedance and circuit fuses or switchgear so related to such impedance that there will be isolation of the supply in the event of a short-circuit.

Recently, a man working in a dangerous situation in an important factory in this area used as a portable lamp a metal lampholder supplied at 240 volts a.c. The two v.r. insulated cables had no cord grip at entry to the holder. The live cable came out of its terminal and the man, examining the holder to find out why the lamp would not light, was electrocuted. For dangerous situations, my Department urges the use of 25-volt safety-type hand-lamps (not requiring earthing) supplied from a transformer which, if portable, should be enclosed in a wooden case in such a way that the only possibility of a 240-volt a.c. shock would be from the flexible cable between wall socket and transformer case. To a man working on a maintenance job inside a metal boiler or tank, this should provide guaranteed electrical safety.

Safety in welding should also not be forgotten. A few weeks ago a welder in this area was working in the boiler room of a ship, where the temperature was 105° F. He collapsed and died as a result of an 80-volt a.c. shock from the electrode. Where welders have to work in confined or otherwise dangerous situa-

tions and alternating current is used, a device should be inserted in the welding cable arranged to reduce the voltage on the electrode holder to about 20 volts when the electrode is parted from the work. Alternatively—and better still—direct current should be substituted.

The incidence of electric shock in factory premises is probably four times as great as the statistics in Form 929 ('Electrical Accidents and their Causes') would indicate. Many occurrences do not become reportable because the man does not cease work. But every one of these unknown incidents is potentially as dangerous as those which have to be reported and appear in Form 929.

Finally, in discussing ventricular fibrillation, it should be remembered that much remains to be determined. The yearly statistics include many instances of resuscitation by proper application of the older methods. We want factories also to introduce the newer Holger–Nielsen method in combination with the rocking-stretcher method. We are convinced that if one of the accepted methods is begun within the first minute following unconsciousness from an electric shock, and the method is properly applied and continued, the chance of recovery is very high indeed. In any factory, there should be a number of men able to administer artificial respiration with sufficient confidence that they will refuse to have the patient taken by motor vehicle to a hospital, and will thus avoid an interruption of the treatment.

Mr. K. M. Mackenzie: Lower operating voltages and automatic switches which monitor the earth circuit are steps towards safety, but they still leave flexible cables and their connectors as the most vulnerable parts of portable equipment. Accidents from this cause would be reduced by:

(*a*) Using flexible cables which can be completely detached from the portable appliance by an 'inlet' plug and socket.

(*b*) Keeping these cables as short as possible and providing special hooks on which to hang them when they are not in use.

(*c*) Keeping record cards showing dates of frequent periodic inspection, test and repair for these cables each of which should carry a serial number.

A few spare lengths of cable permit such a system without laying tools off production.

The B.S. 196 plug and socket connectors referred to in the paper have now been successfully adapted for use on 25-, 50, and 110-volt circuits. They are also available with single- or double-pole cartridge fuses and with an extra contact specially designed for monitoring circuits. All of these types are, of course, non-interchangeable.

I support the author's plea for standardization in this respect.

Mr. F. E. Heppenstall: Some years ago I made a test on my own reaction to a.c. electric shock and found I could stand up to 25 volts a.c. between my two hands, but at this point the pain became quite severe. I think, therefore, that 25 volts to earth may be considered generally safe, but this voltage may easily give sufficient shock to cause muscular reaction which might be dangerous to a man working at a height—who might easily be killed by a resultant fall.

The majority of accidents appear to be due to disregard of the most elementary precautions in the use of electrical apparatus, precautions which are frequently deliberately ignored by those qualified to know better. This disregard of elementary precautions can only be changed by more propaganda about serious accidents. I think also that insurance companies could assist by requiring a heavier premium for installations not shown to comply with an adequate standard.

In his conclusions in Section 4.4 the author advocates the installation of a copper strip around the factory. In most factories, I feel this is unnecessary since the bonding of all cables, conduits, switchgear and building structure with earth plates at the substations and large switchboards should be adequate.

I think that the definitions the author gives for 'extra low', 'low' and 'medium' voltages are unsatisfactory, since they conflict with the definitions of the 'low' and 'medium' voltages in the Electricity Regulations under the Factory Acts, according to which 'low' voltage does not exceed 250 volts, and 'medium' voltage is above 250 volts but not above 650 volts. In proposing other definitions I think the author should try to extend the definitions of the Factory Act Regulations, and I suggest the term 'low' for voltages exceeding 65 but not exceeding 250 volts, the term 'extra low' for voltages exceeding 25 but not exceeding 65 volts and the term 'safe' for voltages not exceeding 25 volts. The latter is in line with coal mining conditions, where 25 volts is considered intrinsically safe.

Mr. R. R. Pattinson: A safety device must adequately fulfil certain conditions if it is to be acceptable to engineers, and it might not be out of place to mention the main ones. In my opinion, a device must: (*a*) not reduce overall continuity of supply, (*b*) work and continue to work with the minimum of skilled maintenance, (*c*) be available at a cost which is not prohibitive, (*d*) be intrinsically safe, and (*e*) not produce secondary effects.

Condition (*e*) perhaps requires some clarification. Recently a power company, at certain times, noticed a marked increase in the earth-leakage current. This was finally traced to a number of pieces of single-phase transportable electrical equipment which had been wired with the connections to the earth and neutral terminals interchanged: the current which should have returned through the neutral conductor was finding its way back through earth.

The author has introduced us to an intriguing earth-monitoring circuit interrupter. I fear, however, that it will not find wide acceptance, but time will show.

Mr. E. C. Scott also contributed to the discussion at Manchester.

[The author's reply to the above discussion will be found on page 447.]

SHEFFIELD SUB-CENTRE, AT SHEFFIELD, 17TH NOVEMBER, 1954

Mr. R. H. Price: In Section 5.3.1, the author referred to the Annual Report (1951) of the Chief Inspector of Factories, where he states that experience appears to justify the figure of 110 volts as a sound compromise for general use. The use of words like 'appear' and 'compromise' in themselves indicate that there is no clear-cut decision on the part of the Chief Inspector. He is only too aware of the snags that can arise in assuming that 110 volts and 50 volts are safe voltages where portable-tool and hand-lamp supplies are concerned.

While the author, who is closely associated with a large industrial organization, has given his paper with particular reference to the industrial field, it should give him a feeling of satisfaction to know that the Central Electricity Authority has adopted as a standard instruction in all contracts that (*a*) a supply of electrical energy at 110 volts single- or 3-phase, with centre points earthed, shall be used for all portable tools, double switching being used for such apparatus when connected, and (*b*) all hand-lamps shall be arranged for 25-volt operation from the 110-volt supplies by hand-lamp transformers.

The National Joint Advisory Council for the Electricity Supply Industry has also recommended that 110 volts r.m.s. maximum with 64 volts r.m.s. maximum to earth for portable tools, and

25 volts r.m.s. with centre point earthed in accordance with B.S. 794 for hand-lamps, be adopted. This recommendation has been approved by the Authority in principle.

I am very pleased that in Section 7.1 the author felt it necessary to draw attention to the lack of clearly defined and specially designed plugs and sockets for 110-volt and 25-volt supplies. It is long overdue that such a study should be given by the B.S.I. and special patterns standardized for each voltage, their shape and colour being such that one can tell at a glance on what system of supply a socket is connected. I have seen a contractor's hand-lamp disintegrate because the plug fitted a socket supplied from a higher voltage than that for which the hand-lamp was intended.

Again, I am glad that the author has drawn attention in Section 7.2 to the necessity for systematic maintenance. Well-planned and well-organized routine maintenance and 'anticipatory fault checks' cannot be too well done. On construction sites, construction equipment is often brought to the site in an appalling condition, and it is difficult to keep control over the state of equipment without some form of maintenance checking. Hand-lamps and portable tools regularly get carried around in contractors' tool boxes and the maintenance engineer is approached only when something has gone wrong. Those are the fortunate cases; more often the fact that something is wrong is disclosed by notification of an accident.

The Butcher system is most interesting, and it is disappointing that simple as the system is, it is not quite 100% safe; it just falls that amount short which will not let one put complete trust in the system as accident proof. The author has drawn attention several times to the inherent danger of men working in the boiler house or in tanks with portable equipment with whatever 'safe' system is used. I think we as engineers, although anxious to make the best and widest use of electrical energy, should always promote the use of the best type of equipment available, irrespective of the source from which it derives its power. In boiler houses there is only one safe supply for portable tools and that is compressed air.

[The author's reply to the above discussion will be found on page 447.]

SOUTHERN CENTRE, AT BRIGHTON, 8TH DECEMBER, 1954

Mr. C. Freeland: The paper is particularly valuable even if it does no more than drive home two points which are at present not sufficiently widely appreciated, namely that the normal standard distribution voltage of 240 volts is lethal—in fact, going by statistics, 50% more lethal than all other voltages combined—and also that means are available to circumvent this deadly quality.

It is distressing to note in Section 3.1, at this date, the 'gospel of despair' concerning ventricular fibrillation. Admittedly, there is no recognized first-aid treatment for this condition, but the researches of Ferris, King, Spence and Williams in the United States, Fisher and Frölicher in Switzerland, Djourno in France and others have given a glimmer of hope, to say the least, that the answer to this problem is there for the finding. The first-aider, in the meantime, by prompt artificial respiration, can try to keep the patient alive until he is proved dead by the only known recognition of death from this condition, namely the onset of *rigor mortis*.

Section 4 is probably the most valuable in the paper since it drives home the importance, where practicable, of firmly bonding all metalwork to the neutral of the supply, thus avoiding dependence on earth current actually entering the soil. The methods illustrated for bonding low-voltage supplies, or for monitoring the earth lead where it is essential to use mains voltage for transportable equipment, are ingenious and, where permanent installation is made, safe.

Before it is possible to receive a fatal shock with orthodox equipment it is necessary for two defects to occur, namely faulty insulation on the portable apparatus coupled with a defective earth circuit. If the means put forward by the author are employed with portable transformers it is easy to visualize other combinations of two defects which would render the apparatus, operating at low voltage and therefore nominally safe, just as hazardous as orthodox equipment.

In this respect it would be interesting to learn what proportion of the recorded fatalities from portable apparatus was caused by 'natural' defects and how many by ill-advised interference, for example changing plugs to suit different socket-outlets. Non-standard colouring of the cores of flexible leads does not assist in this matter.

It would appear that maintenance would have to be even greater than that necessary with standard equipment.

The economics of providing low-voltage supplies are not discussed, but nevertheless must be considered before deciding on any installation. It is suggested that the cost could be considered as an insurance premium against fatal accidents or reportable accidents. As to fatal accidents, figures taken from the annual report of the Chief Inspector of Factories for the year 1951 lead to the conclusion that 2·1% of all fatal accidents were due to medium-voltage portable electrical equipment and that 0·1% of all reported accidents were due to this cause. It appears, therefore, that the justifiable expenditure would lie somewhere between 0·1% and 2·1% of the total expenditure on accident prevention. With this in mind it is suggested that standard equipment at standard voltages, with direct and controlled maintenance, should be employed for normal situations; in conditions of particular hazard, 110 volts with the mid-point earthed, and for situations of extreme hazard 110 volts in connection with the Butcher system as a permanent installation, should be adopted. Low-voltage supplies with portable transformers should not be used in view of the false feeling of security introduced.

Mr. H. Hobbins: I recently had occasion to examine a protective device designed for one portable tool. A connection was made simulating a faulty tool but the device did not break the circuit, although it must be admitted that the earth was still intact, which would have been a safeguard in practice. Also, unless the device was dismantled and a soldered internal link removed, it could not be arranged to monitor the earth connection between the device and the point of supply. The cost was equal to that of a medium-size electric hand-drill, which seems high for protecting one tool. The special lead and connector is also a rather expensive item.

Summing up, it seems that for all but the large installations a centre-tapped 110-volt supply offers the simplest form of protection. To try to press the adoption of more costly and complicated devices which entail skilled servicing is likely to deter users from employing any form of safeguard.

For cases where the more elaborate equipment is justified I consider it should be of a type that would isolate the supply when a fault occurred on the tool as well as when there was a break in the earth continuity.

Mr. H. Midgley: I should like to make a plea for standardization of voltages of portable electric tools. The author has examined the case for 110, 50 and 25 volts, and these three voltages are all in use by large industrial concerns. In my

opinion 110 volts is the most suitable, and—apart from the reasons already advanced for this selection—I would mention that any safety device will not be successful unless it is popular with the people who operate it; I am afraid that portable tools used on 50- and 25-volt supplies will not operate efficiently on account of voltage drop. In fact, in the hands of some operators they may all too easily be brought to a standstill.

Portable tools are used largely by maintenance people and contractors. The Central Electricity Authority, on their construction sites, give contractors a supply at 110 volts for portable electric tools. If other concerns adopt other voltages and provide these supplies the contractors will have an argument for retaining their standard 240-volt equipment. In fact, at one site where a 110-volt supply was given, it was found that the contractor had bought 110/240-volt transformers, and was using his 240-volt equipment in this way. I submit that if there are three standard voltages it is an encouragement to the contractor to buy auto-transformers tapped at 25, 50 and 110 volts and use them with 240-volt equipment, thus defeating the ends of a low-voltage supply.

It is already agreed that a low-voltage supply should be adopted in the interests of safety. The addition of protective gear on top of this precaution means considerable maintenance work, if the protective gear is to remain in proper working order continuously. Those who have had experience with protective gear know the amount of work involved in order to ensure that it will operate at the very time that it is needed. If it fails to do this any money spent on it has been wasted. I would therefore suggest that for ordinary industrial risks the work that would otherwise be done in maintaining protective gear should be transferred to maintaining the portable equipment itself and this, with reduced voltage, would give a reasonable degree of safety. In special circumstances, however, such as working with portable electric tools in boilers and tanks, there is in my opinion a case for some simple form of protective gear on the lines of several schemes which are mentioned in the paper.

Mr. L. H. Fuller also contributed to the discussion at Brighton.

[The author's reply to the above discussion will be found on page 447.]

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 13TH DECEMBER, 1954

Mr. J. B. Lancaster: In examining the degree of risk which is reasonable the author uses the phrase 'which any insurance company would be pleased to accept', and I am sure that nearly all of us who have to deal with this problem in practice will agree with such an approach.

At the outset, I should like to associate myself clearly with the author's views on the right voltage for portable tools. It is gratifying to note that the electrical branch of the Factory Department also continues to recommend 110 volts as that providing a reasonable assurance of safety. I feel that their stand against any movement to reduce the recommended voltage has been an important factor in obtaining the increasingly common use of 110-volt tools, to which they refer in 'Electrical Accidents and their causes: 1952'. A change in their recommendation would, I feel, have actively discouraged such improvement. From the same publication it is of interest to note that in the mining industry, where for some years no portable apparatus has been used on voltages exceeding 125 volts, the record of serious accidents is negligible, notwithstanding that the environment is usually of the sort associated with a high shock risk. This also, I think, lends force to the author's arguments.

The additional simple precaution of using the Butcher system in high shock-risk areas is one which appeals to me as avoiding the very great difficulty of using special tools in such areas, as we feel that it is almost impossible to ensure that the wrong type of tool will never be used.

In dealing with the disadvantages of 50-volt unearthed tools, the author has referred to the danger arising from involuntary movements. Dalziel, in a paper, puts this problem very aptly* when he says that 'Currents slightly in excess of an individual threshold of perception might produce apprehension, fear, or other adverse reaction, and the surprise might be associated with an involuntary movement resulting in loss of balance, a fall or contact with a dangerous mechanism, with serious injury as an after effect'. In the same publication he reports a number of experiments of which one, reporting the results of tests on 26 men holding a portable drill, is of particular interest in the present context. He gives the following figures on perception currents.

	Minimum	Mean	Maximum
Current, mA ..	0·6	1·2	1·8
Volts (r.m.s.) ..	1	2·1	3·8
Resistance, ohms	1 160	1 810	2 970

* 'The Threshold of Perception Currents', *Electrical Engineering*, July, 1954.

The very low values of perception voltage may be surprising but will readily be appreciated by anyone who has carried out the simple test often described and demonstrated in this area by Mr. Picken. From these test figures it is apparent that the 25 volts to earth which is quite likely to be present on a 50-volt unearthed tool involves a probability of a shock well above the perception level. Dalziel also refers to the serious decrease in perception currents with persons having unhealthy hands or where an open wound is present. In view of this evidence it seems clear that, far from 50-volt unearthed tools being safer than 110-volt earthed tools, they may in some instances be more dangerous.

As to portable lamps, I cannot support the author's contention that a voltage as low as 25 volts is necessary, whereas 110 volts is quite suitable for portable tools. It is quite possible to purchase portable lamps with substantial and durable insulation, and, again, provided that there is regular maintenance and inspection, the probability of a dangerous situation arising seems remote. In the organization with which I am associated, a large number of ordinary pear-wood portable lamps is used, and, apart from a few withdrawn from service owing to cracks appearing in the wood (and it is of interest that we have not yet experienced breakage of the wood) no lamp has been found to be in a dangerous condition. Such potential dangers as have come to light have all been associated with damage to or deterioration of the flexible cable, and the risk here is exactly similar to that with portable tools. If it is borne in mind that on our 110-volt system we have in use 1 350 sockets and 230 transformers, it will be appreciated that the cost of installing a separate system of 25-volt sockets and fixed transformers would be substantial. It would thus only be possible to use 110/25-volt portable transformers, which would be a nuisance to the user and would certainly do nothing to improve the regularity with which portable lamps are returned for inspection. In fact, for a cost considerably less than that of the extra transformers, we could adopt a more substantial rubber-insulated lamp, which I feel could be regarded as virtually indestructible.

One is sometimes tempted to wonder whether the very low voltages recommended for portable lamps are a legacy of the days when portable lamps usually consisted of a metal lamp-holder on the end of ordinary twin flex, which would doubtless cause a considerable number of accidents. In those days the majority of portable tools would be used on 230-volt circuits.

and as it would only be practicable to reduce the voltage on portable lamps, there would be no reason for not going to as low a voltage as possible. In these circumstances a later decision to reduce portable tool voltages would necessarily involve the setting up of a separate 110-volt system, and one can see that the dual voltages for lamps and tools may thus have arisen for historic reasons. Would the author care to say whether he would undertake the expense of changing to 25-volt portable lamps already in use on a 110-volt system with fixed transformers, always assuming that all equipment is adequately maintained?

Turning lastly to transportable equipment, we feel that this is the most difficult type of equipment to deal with: on the one hand the voltages used are more dangerous, but on the other the equipment itself cannot usually be misused to the same extent as portable apparatus, can be more liberally designed, and is usually in contact with the surrounding earthed area to about the same extent as the operator. The reports of the Chief Electrical Inspector of Factories do not clearly segregate accidents on mobile equipment, but one gathers the impression that there is not the same serious risk as with portable tools and lamps. In our experience, shocks from mobile equipment are usually associated with the flexible cable rather than with the apparatus itself, and such risks as do arise are frequently occasioned by the apparatus running over its own cable. Up to the present we have therefore used flexible cables embodying double earth connections, one of which takes the form of a braided earthed screen embodied in the tough-rubber sheath of the cable, thus ensuring that any damage to the cable must of necessity set up a fault condition, causing disconnection of the complete equipment from the supply. At the same time we take such steps as we can to discourage movement of the equipment with the cable alive, e.g. by keeping the cables as short as possible.

However, the author's recommendation is obviously a potential improvement on the degree of safety we achieve, but leaves us still with the question, Does the lack of safety in our present system justify the considerable expenditure and additional maintenance which the installation of monitored earth-leakage circuit-breakers would involve? At present we have some two hundred 400-volt plug points installed, which will give some idea of the cost of making the modification suggested. Some economy could no doubt be achieved by adopting long trailing cables to reduce the number of plug points, although in view of our past experience the wisdom of this step would seem somewhat doubtful. It is also relevant to this consideration that in general the more simple the apparatus the greater the reliability.

One of the disadvantages of our present system is the relatively short life of cables with the braided screen, but we inspect and thoroughly test all mobile equipment on site once every month. I wonder if the author would express his views on the adequacy of our present precautions.

Finally, the author quite rightly emphasizes the need for adequate maintenance. He will be interested to know that in instituting our system of 110-volt tools and portable lamps some 5 or 6 years ago, we decided on a maintenance period of two weeks. Although we have several times examined the possibility of extending this period, the repairs found to be necessary, even after so short a time, make us reluctant to alter the maintenance interval. The most usual requirement is to replace or repair by vulcanizing deteriorated flexible cable.

Mr. H. U. Hayes: I think that in small workshops one can afford to install the extra-low-voltage extension lamps, since few accidents seem to come from the lampholders themselves but instead from the flexible cables being suspended from or wrapped around iron framework and thus being prone to fracture of insulation and energizing of unearthed frameworks.

I think it is necessary to abolish full-voltage portable tools by banning their manufacture; for factory use the pneumatic tool provides the complete answer.

Mr. W. S. Morris: The organization with which I am concerned has embarked upon the 50-volt system for portable hand-held tools; the initial permanent installations have been provided in some new workshops and in a boiler plant, and we now await the first 50-volt portable tools.

We have been using 25-volt mains-supplied hand-lamps for over 10 years. My experience with these hand-lamps under refinery conditions does not permit me to agree to their use at 110 volts, as suggested earlier in the discussion. One particular risk with a hand-lamp is that after it has failed its user will grope in the dark for it and if the glass is broken his fingers can contact the live filament ends.

Refinery process units are only shut down for large-scale maintenance at long intervals, perhaps only as often as statutory requirements demand. Operating periods exceeding 12 months are common. In these circumstances we do not always feel justified in providing 25- or 50-volt permanent installation on the process units, and are content to take in portable transformer units during the maintenance operation.

The decision to adopt 50 volts is in line with Group recommendations, and it is most interesting to find that very considerable amounts of equipment at this voltage are going to our associates oversea.

A refinery does not require portable tools on the same scale as a manufacturing industry; further, the nature of refinery operations demands the usage in many cases of compressed-air equipment.

We feel that the 50-volt equipment will give us that little extra safety over 110 volts and that its robustness will compensate for any inconvenience due to heavier cables and larger plugs, and at the same time eliminate the necessity for earth-monitoring arrangements and earth-leakage tripping devices. In view of the necessity of using equipment outdoors and perhaps in contaminated atmospheres, we have wondered whether the initial tripping times for these earth-leakage devices will actually be retained.

For the portable equipment which it is not practicable or expedient to operate at 50 volts we propose to carry on for the time being with the Butcher system, which we have employed in a small way. In this respect I should like to have the author's opinion as to the advantage of a 110-volt Butcher system over a similar 240-volt system. I cannot see that one loses a great deal, in fact one authority states that the higher the voltage the quicker is the earth-leakage circuit-breaker operated.

Transportable equipment is not a major worry, but we are looking into it and the author's earth-monitoring system will receive full consideration in this instance, since it will be used generally in places where a fair measure of control will be available.

We all agree about the necessity for good maintenance, but I find in dealing with a large area that it is very difficult indeed to attain the regular coverage of every individual item of equipment; that is an added point in favour of the 25- and 50-volt system.

The author's remarks upon the availability of industrial plugs are commended; anything that can be done to produce some form of standardization would be greatly appreciated.

Mr. N. C. B. Carrick: The organization with which I am associated has also adopted 50 volts. We started using low-voltage tools in 1938, and there must be in use some 8 000 equipments, all of which are operated at 50 volts. The supplies are derived from the secondary of a fixed transformer and fixed wiring with the centre tap earthed, so that we restrict the possible shocks to 25 volts. Occurrence of shock between terminal and terminal is very unlikely. We do not claim that

our system is absolutely safe under all conditions, but we feel that in our hot, damp and difficult working conditions we have been right in attaining the additional safety which 50 volts gives. I think it is quite clear from the remarks in the author's paper that there is an advantage from the safety point of view with 50 volts. It is said that this makes the installation very expensive; 'very' is a relative term in that respect. What we find is that our fixed installations cost something like 10% more than if we had them at the higher voltage. We expected complaints of loss of power because there is always the individual who tries to stall the tool he is using, but there was only a little grumbling at the beginning. We do not find that use of a 50-volt system gives trouble owing to lack of power caused by voltage drop.

It seems to me a little illogical to adopt 25 volts for hand-lamps because it is a safe voltage and then go to 110 volts for portable tools. In my experience a hand-lamp is not as serious a risk as a portable tool, for the good reason that with most of the jobs done in our factories the hand-lamp is not held but hung up, whereas the portable tool is held the whole time it is in operation.

I know people say using a 1 in drill is difficult; I agree but am not claiming that a 1 in drill is a portable tool. I think a 1 in drill should be used on a clamp, since it is much too difficult and heavy for the average man to hold up safely.

With regard to transportable equipment, we are developing a monitored-earth system. We have not a lot of transportable equipment, but we feel that the monitored-earth system gives the greatest degree of safety without very much expense.

Mr. S. A. Lewitt: In the organization with which I am associated we have found plugs and sockets which give absolute non-interchangeability on the 50-, 110- and 240-volt systems. We achieved this by getting all the types of plugs and sockets we could from the various manufacturers, and after mounting them we tried all the plugs with all the sockets to see which would go, and which would not.

The author has no doubt done something similar, and it would be interesting to know to what extent he was successful.

Some months ago a Factory Inspector came to pay us a visit well and truly bandaged, and when I inquired what had happened he said he had been using a portable voltmeter when doing some testing and there had been a breakdown in insulation inside the voltmeter which had exploded in his face. I asked if he had been using test leads incorporating what was recommended, namely h.r.c. fuses in the leads. He said he was sorry that he had not. I should like to ask the author what he would recommend for safety and protection on portable apparatus of this kind, i.e. testing equipment. We have explored the market trying to find test leads incorporating certified h.r.c. fuses, and so far we have not succeeded, so we use some home-made ones, and some we can buy, but the latter do not incorporate certified fuses. I should like to know what the author uses in his organization.

Mr. E. P. Hill: The suggestion by an earlier speaker in this discussion, that hand-lamps are less vulnerable than portable tools in the case of a fault, does not always apply. One example of this occurred when a hand-lamp had been fixed between two heavy bus-rings of a large electric generator, and the flexible had been damaged in the process. This caused the machine to become alive and a cleaner was instantly killed as he touched the commutator.

My own experience over many years causes me to support the view that the flexibles are more frequently the source of trouble. Portable apparatus can be designed to be practically foolproof, but flexible leads which are equally vulnerable require greater care both in design and maintenance.

The subject of shock and its effect on the heart and muscles indicates from Figs. 1 and 3 of the paper that an a.c. supply i definitely more dangerous to life than the corresponding simila d.c. supply. As supply frequency increases above 50 c/s th subject can 'release hold' more easily, and at lower frequencie down to direct current the same applies. This confirms m experience in comparing the effect of alternating and direc voltage. The body resistance is higher to direct voltage, an during long experience of large testbeds of electrical manu facturers I found that alternating current caused the greate number of fatalities. The increased use of a.c. supplies i homes and factories therefore calls for greater appreciation b users of the dangers involved by the misuse of electrical apparatu and its connections. The questions of waveform distortion an the possibility of the 250-volt alternating voltage rising to ove 400 volts owing to faults, as well as the difference between max mum value and r.m.s. value, must be recognized.

In visiting small workshops which do not have trained electri cians in charge, I have been surprised by the laxity of metho in which earthing of apparatus is carried out. In certain case the earthing cable had been disconnected and those in charg were unaware either of its significance or the possible conse quences. The human element enters into all these problem and can be reduced only by adequate and frequent educatio such as is associated with the reading of this paper. It therefo merits support by those interested in the development of th electrical industry in the service of this country, and is a timel contribution to this end.

Mr. G. H. Currie: Possibly a more usual source of trouble tha the flex is the method by which it is anchored. I think it cal for greater care in design than we usually see, especially in th smaller apparatus.

A rather unusual piece of transportable apparatus that ha to be supplied at 240 volts may be of interest. This was a fir engine, or 'fire appliance' as it is called by the N.F.S. The are often fed via a 'snatch plug' at the rear, with circuits fo charging, engine starting, and recording, all usually at extra-lo voltage; but eventually these appliances were supplied fitted wit engine heaters rated at 750 or 1 000 watts, on a 230–240 vo supply. I asked the Fire Brigade engineer to have the heate changed to 110 volts, but apparently it was a little late in the da for this and I had to feed a 240-volt circuit via the 'snatch-plu into the appliances.

A monitoring-earth circuit was used (at 12 volts), the auxilia earth lead being insulated right up to its earth electrode to ensu that the main earth electrode was not by-passed. The 240-vo circuit was tripped if the earth circuit was broken anywhe including, of course, the breaking of the circuit when the applian moves off away from its 'snatch-plug'.

Mr. A. G. Scott: Some of the previous speakers have state that they see no reason why portable hand-lamps should b operated at 25 volts when portable tools are operated at 110 vol Surely it is our duty to reduce accident risk to a minimum eve though it may mean that facilities have to be provided to supp dual voltages at all points in a factory. Another point in favo of 25-volt hand-lamps is that they can be purchased complete moulded in rubber and therefore no earth-continuity conduct is required, but this degree of protection for portable tools 110 volts is not yet available.

In the particular organization with which I am associat every single socket-outlet is a standard fitting operating 110 volts (55 volts to earth), and small 110/25 volt 120 VA tran formers are provided which can be plugged in at any socke outlet position to supply two 25-volt hand-lamps.

Mr. M. J. Horsburgh: As pointed out in the paper, failure the earth core in the flexible cable increases the risk of shoc A normal maintenance test of continuity, insulation resistan

and visual inspection cannot always detect an earth core which is reduced to a few strands; therefore the test should include circulation of a heavy current through the earth conductor for a short period in order to burn out or prove the efficacy of the conductor. To this end a convenient test panel for current circulation and insulation routine could be developed and equipped with socket-outlets in use in the factory, which would reduce routine testing to a very short period for both portable and transportable equipment.

In the larger factory where a stores system exists for the issue of portable tools such a test panel, plus coloured lights to indicate the condition of the equipment under test, could be installed at the point of issue.

Mr. T. V. Lironi: An interesting point arose earlier this year when Electricity Boards received a Government circular from local authorities, urging them to provide electricity supplies to houses on new estates at an early stage in their construction. The implication was that with electricity available, it could be used to speed building, particularly by the use of portable tools.

It requires little imagination to visualize the conditions under which such tools would operate. Earth-leakage trips or monitored-earth conductors would have no place in such a set-up, and the accident risk would be extremely great.

I raise the matter to illustrate the prevalent outlook, even of responsible bodies, regarding the use of portable tools.

In my opinion, building sites should be treated as hazardous situations. Tools should operate at 110 volts and stringent precautions should be taken.

Whilst I agree that we do not want to have different voltages for every set of conditions, I do feel that building sites should be regarded as dangerous situations requiring the use of reduced voltages for portable tools and appliances.

[The author's reply to the above discussion will be found on page 447.]

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 18TH JANUARY, 1955

Mr. A. J. Coveney: I would point out that instances have been known when a voltage as low as 6 volts has proved fatal to a cow—a matter of some importance to distribution engineers when earth faults produce voltage gradients on the ground at the foot of overhead-line poles. My purpose, however, in mentioning this is that, with the increased use of electricity in agriculture, and particularly the milking business, most careful installation and maintenance of all electrical apparatus is essential, and the wall-mounted monitored-earth circuit-breaker unit appears to provide the answer to this danger.

The Factory Department's reports of fatal accidents show that there are more fatalities in the domestic world than in factories, undoubtedly owing to better supervision and maintenance of the equipment in the latter, but it is a significant fact that the majority of these fatalities are due to faults in the cable and flexibles. I therefore suggest the use of an additional inlet plug and socket on the apparatus, as well as the outlet socket from the supply, thereby providing a standard form of flexible connection. In factories this would enable the maintenance engineer to check and replace these cables readily, without any loss in production.

I am glad to know that the author supports the B.S. 196 plug and socket. Hundreds of thousands of these are in use and experience has proved their efficacy. It is possible to obtain B.S.196 metalclad units with the key and key-way arranged so that there can be three patterns non-interchangeable, and therefore suitable for three different voltages. Unfortunately, with the increased number of the many new types of plug, it is possible for a single-phase 2-pin plug to be inserted erroneously and accidentally into a 3-phase socket with fatal consequences, and works engineers should make a thorough investigation of this possibility to ensure that it cannot arise in their works. Fused pins are also available with this particular pattern of plug and socket, and I do not agree with the author that there is any inconvenience in using only one manufacturer's products. The standardization of one pattern throughout a works is a most desirable feature for safety reasons.

With regard to the monitored-earth circuit-breaker units as shown in Figs. 9 and 10, I would point out that there is a danger of a wireman connecting up the two earth leads from the circuit-breaker unit to the portable apparatus, either as one cable or joining them together at one earth point on the portable apparatus. The author clearly specifies two separate earth terminals, but how much portable apparatus is provided with two earth terminals? If the two earth leads are joined to one terminal and there is a bad contact, the circuit-breaker will test out satisfactorily but be unsafe in operation.

A further point is the possibility of using an earthing resistance in the neutral point of the transformer. With suitable values chosen, it is possible to limit under earth-fault conditions, voltage rise to not exceed 50 volts on the earth metal. Co-ordination of transformer size, neutral resistance and the apparatus is necessary, however, but may not be possible in certain load centres of the factory.

Finally, with the ever-increasing demands for the fitting of suppressor units to all portable tools, I would ask the author whether he has considered the additional dangers from these connections.

Mr. F. Porter: As I see it, there is no such thing as 100% safety under all conditions of service. More particularly so, in relation to the use of portable tools and equipment. It seems to be taken for granted that 100 volts a.c. is the nearest to an ideal voltage for portable-tool operation. I wonder whether there really is all that amount of difference between 100 volts and 240 volts a.c. as one might at first imagine? A lot depends, as I think the author indicates, on the state of health of the 'shocked' individual and the dryness of the position concerned.

In Section 2.2 paragraph (*c*) the earth wire seems to be the culprit. It is often so, usually because earth wires are not mechanically strong enough for the job. In my view nothing short of a main earth-continuity system, installed with the electrical circuits, from which an independent earth wire of suitable size, yet flexible enough to meet conditions of service operation, will do. This earth wire should be attached to the machine, which would be unable to operate without it. This 'having to do something first' before one can use a machine would educate the user and make for an increased safety factor.

Bad workmanship is inexcusable, and should be treated accordingly. We are playing with possible death, long before the allotted span, and a heavy impression should be made upon the minds of all concerned.

Another point worthy of consideration is the need for the improvement in design of portable equipment. Consider, for example, an electric drill. Why should not the handles be covered with a heavy-duty insulated material—now available to withstand hard usage—in order to reduce the risk from grasping the equipment when in use? This part of the equipment is where one takes the weight and is firmly under the grip of the user. There is a large difference between receiving a shock when

firmly holding a machine, as against just touching the machine slightly by hand.

Fig. 4 is useful in that it confirms the need for lowest possible impedance from equipment to earth, via a sound earthing system. The author emphasizes the need for efficient earthing and bonding in his last sentence of Section 4.2.

The insulated neutral system mentioned which may apply on a minority of power supplies is positively dangerous, as the author implies, and is not by any means a solution to safety problems under review.

At one point the paper packs a lot of home truths into a few lines, namely in Section 4.4. Here lies the root of maximum safety, and it can be obtained only at a price, i.e. the use of the very best systems available for solid earthing and bonding, giving continuously minimum impedance values all along the line. Automatic features are almost useless, in most cases, unless accompanied by the provision of this sound solid mechanical and electrical earthing system.

Giving basic principles, the author carefully spotlights methods of protection.

Constant reference is being made to the liability of the earth-continuity conductor being broken and the risk involved. All this strengthens the need for more solid form of earthing, using flexible conductors only where absolutely necessary.

With reference to Fig. 8, would it not be advisable for the earth connections in the multiple-socket box to be fed from a solid earth-continuity and bonding system?

Mr. L. L. Emmett: On the use of tripping apparatus to control earth-leakage faults the major use would be in the works departments, laundry, etc., where the apparatus can be fixed to control a number of outlet points.

One of the major difficulties in the hospitals is the lack of fundamental knowledge of the correct use of portable apparatus, and even sterilizing by boiling of connections and equipment is often indulged in by the nursing staff.

It does seem that statutory requirements should now be made and enforced that all portable apparatus should be efficiently earthed by a cable having 50% heavier current-carrying capacity than the live or neutral conductors, in order that the mechanical and electrical continuity will outlast the current-carrying parts of the same cable. It should also be incumbent upon all employers to record the testing and maintenance of all portable electrical equipment by means of test apparatus designed to pass a minimum of 100% excess current or 10 amp, whichever is the greater, through the earth lead of the flexible cable.

The continuity test by a lamp or tester in circuit is to be deprecated as being likely to give a false impression of security. One strand of the earth flexible cable would pass this test if left still in circuit.

In all circumstances where shock hazards are likely, I suggest that the earth continuity should be maintained by an independent earth conductor back to an established earth system as distinct from the normal casing or covering of the conductors. In this respect, the earth continuity wire installed in some types of cables has much to commend it.

Much of the safety factor is bound up with the efficient maintenance and correct wiring technique, and I would urge the fitting of double-pole switches on all portable apparatus.

Where transformers are used having no tapped centres, I think that one pole should be earthed and the polarity marked. This is especially necessary for apparatus used in operating theatres in order to ensure the correct wiring of surgical lighting units and all single-pole control switches should be fitted on the live side.

Mr. D. Marshall: The author agrees that a properly designed 50-volt system is extremely safe, but rejects it in favour of the 110-volt system, on which there is some risk, his main points being performance and cost.

I have had experience of the operation of 50-volt tools in a large factory, formerly using 240-volt tools, and on questioning several users on their experience the answer in every case expressed satisfaction with the performance of the 50-volt tools, all normal requirements being met.

The author might, with advantage, have gone into more detail on the question of cost, as he gives the impression that a 50-volt installation is considerably more expensive than one for 110 volts. Comparative costs which I have seen quoted indicate that this is not the case, and in fact the difference in cost is marginal.

It would be a matter for regret if potential users were dissuaded from adopting the 50-volt system owing to fears about its practicability and cost. The extent to which this system is used at present should be sufficient to allay these fears.

Mr. H. Mounsten-Harrison: In all large factories the electrical engineer is responsible both for the quantity and maintenance of such equipment as may be used. However, many small works and contractors do not employ an electrical engineer, or indeed a full-time maintenance electrician, and they are therefore dependent upon the services of a local man who is called in from time to time when things go wrong. It is here that the greatest danger arises in the use of portable electrical equipment, since it is never serviced and never checked unless it refuses to work, and sometimes the electrician is called in too late to prevent an accident.

As the author states, two-thirds of the electrical fatalities which occurred during 1951 took place at voltages below 250 volts, and it is a disturbing thought that this proportion has not altered, despite all the efforts of those concerned during the past eight years. In fact, it remains alarmingly constant, and an everlasting reminder of the need for a new outlook on this problem.

The author gives three new definitions of voltage—extra low, low and medium—and for those accustomed to the existing definitions this is confusing, since low voltage normally includes 250 volts and medium voltage includes 650 volts.

If it is accepted that the only safe method of working is to reduce the voltage to 25 or 50 volts, we are faced with the problem of either purchasing and installing a large number of fixed transformers, or alternatively using a 230/50-volt transformer fed from the main supply through a socket-outlet and flexible cable. In the first case the cost would be prohibitive in a large works, and the second case is just as dangerous as well as being far more cumbersome. The relative weights given in Section 5.2.2 do not always obtain, since in my experience the lower-voltage equipment is much heavier. For example, a 230-volt $\frac{1}{2}$-in drill weighs 11 lb, while a similar 25-volt drill weighs $19\frac{1}{2}$ lb and its associated transformer weighs 25 lb, giving a total weight of $44\frac{1}{2}$ lb.

A further problem with low-voltage socket-outlets fed from a fixed transformer is the type and size of the outlet to be used. If any of the standard plugs and sockets are used, someone is sure to plug in a 50- or 110-volt tool into a 230-volt socket with disastrous results.

I entirely agree that 25 volts ($12\frac{1}{2}$ volts to earth) should be used for portable hand-lamps, and we have adopted this practice for these lamps and universally for all small fixed adjustable lamps on machine tools.

The author has given a description of several well-considered monitoring circuits and schemes, but I feel that their use must be confined to the large factory installation where there is skilled attention to keep them in order. I do not think they are suitable for general use where they could meet with the ill-usage and rough treatment that is meted out to portable equipment on

building sites, etc. In these modern times, we are apt to overlook direct current, since its use is certainly not as widespread as in former times. This is probably why it is not considered in the paper, but for certain applications it has all the advantages and none of the disadvantages of alternating current, particularly 240 volts a.c. Some years ago I was associated with a large works in the chemical and textile industry, where we used 110 volts d.c. universally for all socket-outlets and portable apparatus. Although it is not 100% safe under all circumstances, I have never heard of any fatality occurring from 110 volts d.c., and although many of the situations where this equipment was used were in wet and steamy atmospheres we never experienced any trouble. I feel that, under similar circumstances, this type of supply has much to commend it.

The emphasis seems to be on regular servicing and maintenance, and we have made it a regular practice to log the test results obtained from the periodic checking of all our portable equipment. This gives us valuable information on its condition.

Mr. A. R. Rumfitt: Previous speakers have drawn attention to the engineering and economic implications of the author's summary of the safety aspect of equipment in industry, but I submit that there is a third factor, namely the legal aspect of portable electrical equipment.

Whilst we may take pride in the efficiency of schemes embodying low-voltage installations and the special safety factors which have been proposed, there is little doubt that the impetus to develop on these lines has been derived from the post-war revision of the laws of compensation. The paper may be regarded as an endeavour to provide a safe system of working within the meaning of the relevant Act. Therefore, I feel that the methods proposed for checking the efficiency of the safety devices provided fall short of what would be required in law to prove that precautions have been taken when considering any specific accident arising. Surely the system of periodic checks of earth continuity do not cover the day-by-day use of portable electrical equipment. A system of daily checking is required. One system which has been adopted by a large user of portable electrical equipment is to have all portable tools returned to a central stores at the end of each working day, and as these are drawn out on the following day for use, they are handed over a metal-topped counter and the 3-pin plug on the apparatus is connected to a special low-voltage supply point which checks the earth continuity by means of a series-connected lamp. Whilst this method is open to criticism, the fact remains that some system on these basic lines must be adopted in order to prove the intrinsic safety of the apparatus. Failure to prove the existence of the earth connection will undermine the valuable steps which are recommended by the author.

[The author's reply to the above discussion will be found on page 447.]

WESTERN UTILIZATION GROUP, AT CARDIFF, 24TH JANUARY, 1955

Mr. J. H. Thomas: It is agreed that a regular and systematic method of testing all portable electrical equipment is most desirable in any industrial concern. Detailed records should be kept, and any item of equipment failing to measure up to the requirements of the test should be withdrawn from service.

What steps would the author advocate being taken by the occupier to ensure that equipment brought to his premises by a contractor is (*a*) suitable for use, and (*b*) safe for use?

Mr. E. Sutton: I do not believe that the study of electric-shock effects has reached the stage when anyone can specify what is, or is not, a dangerous quantity, and until this is established beyond all reasonable doubt, any design based on a specific figure must be suspect. I therefore suggest that this question must be judged at present on strictly practical grounds. In my view this should be the 'let-go' current, for, in an accident, you cannot rely on someone being at hand quickly enough to give aid.

No device has yet been produced, or is likely to be produced, which will guarantee safety under all circumstances, any more than safety is guaranteed by efficient earthing and proper fusing in the conventional way. These devices can only affect the degree of protection, and because they reduce the risk with mains-operated equipment they are well worth adopting. They will never be a substitute for the reduction of the voltage to a value which is unlikely to give rise to serious risks of shock.

For the same reason the standard of maintenance and discrimination in selection of apparatus needs to be of the highest. Too little attention is given to this, for, in my experience, the accessories, and in particular the plug, give rise to the greatest number of accidents. The cord grips of plugs are particularly vulnerable; no design has been produced to equal the safety of a rubber plug which is moulded to its flexible cable.

Legal questions were raised, and it is necessary to point out that, whilst Regulation 21 permits 'earthing or other suitable means' to prevent metalwork becoming charged, Regulation 13 is specific in its requirement to earth efficiently the appliance. This applies to all equipment connected to a source of alternating current irrespective of voltage. There is no exemption from this requirement unless the user is able to persuade the Secretary of State to exercise his powers to direct otherwise. Desirable as double insulation or very low voltage may appear to engineers, the legal requirements for such conditions remain as indicated.

Welding has not been specifically mentioned in the paper although the author no doubt has had this application in mind. Welding apparatus is often used under the worst possible conditions by people who lack the knowledge of the danger these conditions bring. The accident rate has now assumed proportions that no thinking engineer can regard complacently, and in this field alone there is great need and scope for open-circuit voltage limitation by apparatus robust enough to stand the working conditions and sufficiently reliable to minimize the danger of the present system.

Mr. C. E. Dew: I am disappointed that so little space has been devoted to socket-outlets. It is obviously useless to give care and attention to the earth lead of any portable equipment if in fact the earth connection from the socket-outlet is faulty. In this connection it is not sufficient for the regulations to state a resistance for the earth continuity—it is resistance plus current-carrying capacity that matters. The organization with which I am associated has a routine test schedule for all socket-outlets, the resistance of the earth return circuit being measured at 30 amp.

Possibly one of the greatest hazards in heavy industry arises from a piece of transportable apparatus in constant use, i.e. the a.c. static welding transformer. The danger is not from the casing of the transformer but from the electrode holder. So far as I am aware there is no legislation in this country, as there is on the Continent, to insist on a certain maximum open-circuit voltage, although there is apparatus on the market for reducing this until striking the arc.

However safe protected portable tools may be when installed, there is always the possible hazard of electric shock owing to maltreatment and abuse, and constant publicity should be given to training in artificial respiration. It is rather dis-

appointing to note that, whereas the Ministry of Labour booklet *Electrical Accidents and their Causes* in 1950 devoted two pages to this important subject, the information was condensed to one paragraph in the 1952 edition.

Mr. E. R. Radway: I agree that a 110-volt centre-point-earthed system gives a suitable voltage for the everyday use of portable tools, and in my experience the possibility of a dangerous shock at that voltage is extremely remote.

The author seems fortunate in having portable tools concentrated in an area sufficiently small, and of such a user intensity, to justify the establishment of a 110-volt ring main with a continuous earth bar.

For certain applications, such as on building sites and in dock work, portable tools are required intermittently and over a very widespread area, often under bad weather conditions. It is thus essential that portable transformers be used as and when required, the necessary connections to the 240-volt supply being made by qualified electricians, for in most cases even 240-volt plug sockets are not available.

On building sites the Factory Inspector recommends that the portable transformer be used in an insulated box. However, in my view, there is greater safety under the conditions mentioned above in having a transformer directly on the ground and keeping the 240-volt lead as short as possible. The possibility of a fault developing in the transformer winding is so remote as to be negligible, and it is suggested that, as the weight of a 500 VA transformer is stated by the author to be 20–30 lb, any strain on the leads will come on the low-voltage rather than the high-voltage side.

Many transformer manufacturers fit a metal cable grip for the 240-volt connection. It is considered that it would be better to provide an insulated bush with proper segregation of the earth, phase and neutral leads, thus making the possibility of a fault to earth on the transformer casing on the high voltage side, in conjunction with a failure of the earth lead, too remote to be considered, especially as the transformer is not handled during working conditions in the same manner as a portable tool.

Mr. W. S. Evans: No mention is made of the use of low-voltage high-frequency tools from the safety viewpoint. I would like the author's comments on their use when an entirely new installation is envisaged, and no consideration is given to the conversion of existing equipment.

Mr. R. B. Rowson: The paper refers to the possibility of developing core balance to a greater extent than is at present available, and I feel that there is much to be said for this system, since it avoids the possibility of involuntary earths, in effect short-circuiting the trip coil. Furthermore, it does not rely on monitoring or additional conductors for its success. I should be interested to learn whether the author has made any further progress in this matter, since at present it appears that the maximum sensitivity in any switchgear on the market is about 0·5 amp, and for certain duties a lower figure would be desirable.

As an alternative, the possibilities of double insulation should not be overlooked. Since the paper was written, certain progress has been made in this matter, and a draft British Standard is under consideration.

Certain of the connections of the monitoring circuits do not include monitoring the auxiliary earth plate, notably Fig. 10. It would appear that this is quite a vulnerable section of the protective circuit, and the author's comments would be appreciated. The point has been raised in connection with the recent draft British Standard on portable hand tools, and the suggestion that the monitoring should include the whole circuit is being considered.

Mr. G. J. Evans: My attention was directed some time ago to a case in which an accident with a portable drill had proved fatal. It occurred in the smithing department of a large works.

The person concerned stood on a ladder drilling a girder, and on completing the job descended carrying the drill. He stepped from the ladder to a metal plate on the floor, received a shock and fell. The current was switched off immediately, but the man did not recover.

The conditions were as follows: The switch was fitted on one of the steel stanchions, and had a short length of flex and a plug socket connected. The drill also had a short piece of flex and a plug. A long length of flex, 20 yd or more, having the corresponding halves of the plugs and sockets, connected the switch to the drill.

On examination of the circuit, the ends of the phase and earth wires of the long flex in one plug were found loose from the terminals. The earth wire had wandered into contact with the phase terminal at the switch end, thus making the drill case alive.

A standing instruction that any employee intending to use the drill should make a thorough examination of the equipment before connecting may have been honoured more in the breach than in the observance. Had the flex been continuous, needing only to be plugged in to the switch plug, the accident would not have occurred. The intermediate plugs were rather small and hardly suitable for works use.

[The author's reply to the above discussion will be found on the next page.]

NORTHERN IRELAND CENTRE, AT BELFAST, 8TH FEBRUARY, 1955

Mr. J. A. Allen: The author has presented the facts as he found them, and has made no attempt to 'sell' low-voltage equipment to industry. Papers often open with a brief history, and no doubt if this approach had been taken, the reason for 220–250 volts being the accepted normal voltage at present would have been revealed. From 1879, when both Swan and Edison were producing the first carbon filaments, until the early 1900's, the electrical industry was in keen competition with the gas companies. A bright light was the first consideration, irrespective of colour or voltage. At that time, conductor sizes, economical design and safety were secondary considerations.

No doubt the use of the carbon arc also contributed to the establishment of the higher voltages, and as direct current only was in use, the question of safety did not arise. We have only to examine the apparatus in use in those days to confirm the latter point. A transient period followed, first leaving the arc lamps behind and then changing over to alternating current. No doubt because of the established lighting voltage, the 'medium voltage', to borrow the author's term, was convenient for 3-phase distribution and has thus been thrust upon the present generation. I would forecast that any industrial organization or authority changing over to low-voltage portable equipment at 110 volts, with the mid-point of its secondary earthed, is only a few years ahead of the electricity regulations, because, no doubt, legislation along these lines will eventually be introduced.

The organization with which I am associated has, for some years, recommended the use of 110-volt tools (55 volts to earth), 25-volt hand-lamps ($12\frac{1}{2}$ volts to earth) and earth-leakage monitor trips for use with 3-phase 415-volt transportable equipment.

I can only quote one known case of shock from a 110-volt tool, and when this unusual occurrence was investigated it was found that the transformer supplying the defective tool was not fitted with a centre tapping but was earthed on one side of the secondary winding. Further investigation revealed that a bat[illegible]

of approximately 50 transformers had been supplied, and quite a number had been installed without this defect having been observed. All were located and modified. The lesson is that any installation, and especially a low-voltage system, must be properly installed.

We have selected two types of plug top for use on the 110-volt and 25-volt circuits. These are of a design which cannot be inserted in sockets suitable for voltages other than these. It is unfortunate that a British Standard has not been prepared covering socket-outlets operating at these voltages. It is important to note that the 110-volt plug tops are double-pole fused.

Another point concerns a 110-volt transformer which was connected in reverse. Although the transformer was supplied by a reputable maker there was no marking to indicate which were the primary and secondary connections. This was detected on commissioning tests.

Transformers in use are mainly 500 VA air-cooled, and from experience I would state that 250 VA transformers, although suitable for drilling machines and similar small tools, are of inadequate rating where a heavy-duty load, such as an electric hand saw, industrial vacuum cleaner, floor-washing machine or similar plant is likely to be employed and could be used at any time without consulting the factory electrical engineer. There are several hundred 110-volt transformers in the particular works with which I am associated, and over the last six years the total replacement due to faults or burn-outs has been approximately 1% per year. The transformers are alive 24 hours per day, and are switched on the l.v. side.

With regard to 3-phase earth-leakage trips using the monitored earth, i.e. a 5-core cable supplying the equipment, I would like the author's comments on the reason for the relay failure and occasional flashover of the auxiliary contacts. This has happened several times in my experience, and in each case a welding machine was connected to the socket-outlet. In the confusion which follows these occurrences the evidence is often disturbed or destroyed. However, in two cases, investigation revealed that the operator had not made a satisfactory earth return to his welding machine.

A subject which would, no doubt, come under the scope of the paper is the method of terminating 3-core cables to portable equipment, irrespective of the voltage—a point which is frequently overlooked. The earth core should always be left with a little more slack than the phase and neutral cores, since it has frequently been found that, owing to mishandling or a heavy pull on the cable, the earth lead breaks and becomes open-circuited, leaving the equipment with a supply and running apparently normal, but without an earth connection. In the works to which I have referred all portable equipment is on a three-monthly maintenance routine and the result is recorded. This maintenance includes a load test on the earthing conductor. Tools are issued on a check or tally system and are physically inspected and operated each time they enter or leave the tool store.

Table 1 in the paper is most interesting, and I am only sorry that the author did not take this a little further and compare 50 c/s tools with those of a higher frequency. It would have been interesting to have had his comments on the limitations and comparative weights when higher-frequency tools are employed.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. J. W. Bunting (*in reply*): Mr. Buckingham and others later mention the possibility of insulating the handles of portable tools. This might be possible, with the increasing use of tough unbreakable plastics, but to be effective the insulation would have to extend to the body of the tool as Mr. Mellonie points out.

I have no statistics of accidents in America, but I understand that, whilst fatalities do occur on 110-volt-to-earth systems, the accident rates on consumer premises are considerably lower than in this country.

We use h.r.c. fuses on the l.v. side of 110-volt transformers, with further fuses designed to B.S. 1362 requirements incorporated in double-pole-fused plugs to protect individual items of equipment.

Mr. Coleman's proposed modifications to the circuit of Fig. 10 are constructive and should be borne in mind if a British Standard is drawn up. Paragraph (*d*) needs further consideration, however, since the tripping resistor must only be in circuit on test—not in the event of the monitored circuit being interrupted in normal service.

In reply to Mr. Joseph, the tripping time when closing the circuit-breaker on to a fault should not be dangerous, since the closing movement will normally be fairly deliberate and the relay (which is lightly loaded with only one change-over contact) will have operated by the time the circuit-breaker is closed. It is undesirable to change the position of the test button as suggested, since, during test, the connection to the pilot core and the casing of the equipment should be broken before voltage is applied to the trip coil. But if the monitored circuit is broken the relay B releases and the circuit-breaker will trip under the mains supply voltage instead of the 12–14-volt test voltage: moreover the test will have failed to check the continuity through the closed contacts of B. If, on the other hand, the connection to the pilot is not broken, the trip will be shunted by the pilot earth connection and will fail to trip with the test resistor in circuit. Actually, since the paper was written, trouble has been experienced, not with the relay, but with the normally closed contact of the test button and with the flimsy test resistor of one proprietary article. For reliability it is essential that this resistor be fixed in position and the test button should have robust change-over contacts. Existing circuit-breaker units of this type should be modified as shown in Fig. C, and if the movements are lightly

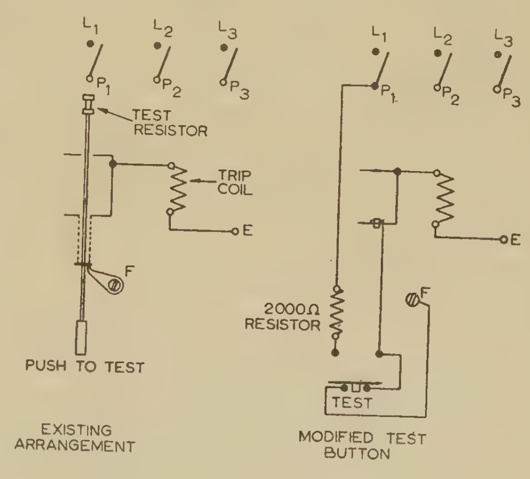


Fig. C

lubricated every three months they will prove reliable and consistent. This perhaps answers the points raised by Messrs. Mare and Morris.

Several of those taking part in the discussion have advocated a core-balance form of protection. Among these are Messrs. Rowson, Mare and Jamieson. Core-balance systems have

proved excellent in coal mines, where, in general, rugged earth connections of low impedance are available and the cost of gate-end boxes and massive armoured and braided screened cables is not prohibitive. For general factory use, however, with industrial vacuum cleaners, balers, etc., a less expensive device is needed, and some of the refinements, such as the pilot-earth fault protection, may have to be forgone. In deciding between core-balance and voltage-operated systems it must be remembered that both depend for their operation on the earth connection being intact when the fault occurs, so that in both cases earth monitoring is essential.

If the operation of a core-balance device is regarded as being similar to that of a fuse which ignores balanced load but responds to an earth-fault current of, say, 0·5 amp, it will be seen that it has attractive features, for if 0·5 amp fuses could be used on a 60 amp circuit we would be reasonably happy—so long as the earth connection was under continuous check. I believe that progress is being made on a simple device on these lines.

However, the voltage-operated unit illustrated in Fig. 10 is logical and provides a very inexpensive solution to the problem. The voltage between the casing and earth under fault conditions is a measure of the danger. To assess the danger a voltmeter, not a current transformer and ammeter, would be used. To eliminate the danger a fast-operating voltage-sensitive trip is the most obvious answer.

In theory, the direct earth connection may short-circuit the trip and prevent its action, but this is tantamount to saying that it may limit the voltage to a figure below the tripping voltage—in which case danger has been averted and the fuses will isolate the fault. In practice the trip invariably operates. Note, too, that the higher the impedance in the main earth path, the higher will be the momentary voltage and the more rapid will be the tripping. The converse holds in the case of core balance, and both the voltage on the casing and its duration are increased with increase of earth impedance.

I agree with Mr. Jamieson that there will probably be a lack of discrimination with the voltage-operated system, although I have not heard of this occurring in practice.

In reply to Mr. Mare, the protection which makes use of a current transformer in the neutral-to-earth connection of the power transformer is simple and reliable, but has the grave disadvantage in a factory that a single fault trips out the main transformer, which may be supplying important plant other than transportable equipment.

The rupturing capacity of the earth-leakage circuit-breakers is not greater than 5 MVA, but short-circuit protection is usually provided by h.r.c. line fuses. No mechanical interlock is provided on the plug and socket, but the circuit-breaker trips instantly when the plug is withdrawn.

Messrs. Tomblin and Sutton leave no doubt as to the necessity for an earth wire with 50-volt supplies.

Mr. Butcher advocates a system of protection which avoids the necessity for a heavy fault current to operate it. His own system ingeniously uses the impedance of the trip coil to limit the fault current, whilst leaving the protected equipment directly earthed. Originally the circuit shown in Fig. 10 was without the direct earth connection at E, and the unit was sensitive to leakage currents of 80–90 mA and was capable of operating under incipient fault conditions. However Electricity Regulation 13 clearly forbids such a system and the direct earth had to be fitted.

In reply to Mr. Wade, some good metalclad sockets have been made to the requirements of both B.S. 546 and B.S. 1363, and one firm has made robust hard-rubber plug tops with single- and double-pole fuses to the requirements of B.S. 1362. Confusion is bound to result, however, if domestic 240-volt fittings are used for low voltage in industry, and it might be better to use B.S. 196 type plugs pending the introduction of the new Standard. The best form of earth-loop impedance testers are those which plug into the socket and employ a transformer to pass alternating current of 20–30 amp through the loop, thus measuring the true impedance.

In calculating the voltage drop on the ring main (Fig. 7), I used the specific resistance at 20° C. Using the figures quoted from The Institution's Wiring Regulations, which allow for temperature rise, the in-phase component of voltage drop works out at 4·7 volts—not 14 volts as stated by Mr. Koh.

I agree with Mr. Mellonie that it is often possible to provide a reliable earth connection of low impedance to a fixed point such as a socket-outlet. But the earth core of the flexible cable and its connections cannot be guaranteed. That is why it is necessary to use low voltage or earth monitoring.

Mr. Rodway's later suggestions regarding portable transformers should prove helpful to those who, like Mr. Robinson, have to resort to this method of obtaining low voltage.

Mr. Picken speaks with first-hand authority on physiological data, and it is interesting to note his conclusion that use of 110 volts with mid-point earthed is the most practical way of obtaining maximum safety. Interesting points are raised by Mr. Binns in favour of 50-volt operation for medium and small personal tools, but his arguments are based on the assumption that 50 volts is very much safer than 110 volts, whereas Mr. Picken's experience leads him to believe that any improvement is marginal. His maintenance notes are very sound, particularly (*b*) (ii), which is often overlooked.

Mr. Light puts his finger on a few of the many omissions from the paper; I must confess that, in suggesting that battery-operated equipment was safe, I was forgetting the 30 μF 'booby traps' charged to 2·5 kV and used by electronic engineers to discourage the uninitiated. With regard to the earth-leakage circuit-breakers, the proposed 500-ohm resistor in the pilot core would reduce the sensitivity of the trip by a factor of 25 : 1. Thus the modification put forward would guard against the combination of faults (*a*), (*b*) and (*c*) but jeopardize the normal tripping action when, as is much more likely, fault (*c*) occurs alone.

Messrs. Merrill, Carrick and Marshall have their feet on very solid ground when they state their preference for 50 volts, since it would be difficult to imagine safer or better maintained installations than those to which they refer. They have planned their installations with local transformers and with plenty of sockets to get the supply to the tool, so that voltage drop is not troublesome with the hand tools in common use. However, I am certain that there is some misunderstanding when they compare costs and they state that such a system is only 10% dearer than one at 110 volts. Whereas they use as many as 20–40 sockets fed from a 1 kVA transformer (I quote Mr. Thornton at the London discussion), we would require fewer in the same area. Moreover, in our latest factory we are distributing at 110 volts from 5 and even 10 kVA transformers, and it is well known that one large transformer costs much less than a number of small ones having the same output. For the same percentage voltage drop we can transmit power 4·8 times as far over the same cables as would be possible at 50 volts.

Messrs. Cahm and Price provide interesting information on the lead given by the C.E.A. in the use of 110-volt tools and 25-volt hand-lamps on constructional work. It should be noted that they use l.v. transformers of up to 25 kVA rating. Mr. Midgley is even more trenchant in his support of 110 volts and his timely plea for standardization of voltage.

Messrs. Murgatroyd, Freeland and others rightly stress the importance of immediate artificial respiration after shock, which should continue until the subject recovers or is proved dead.

I think the detachable cables advocated by Messrs. Mackenzie and Coveney might have a disadvantage, for if the unshuttered socket end became detached and was left trailing in a wet area it could lead to danger. But the adaptation of B.S. 196 has resulted in a useful range of robust plugs and sockets covering most requirements, and fused plugs and sockets are envisaged for 3-phase monitored circuits.

The introduction, for this particular paper, of a new set of definitions is regrettable, but Messrs. Heppenstall and Fuller will agree that, when we speak of 'low voltage' equipment, we do not mean equipment at any voltage up to 250 volts a.c. to earth. Moreover, it is the voltage to earth which is important in considering portable tools, etc. This was brought out in the definitions.

In confirmation of Mr. Hobbins's view, the earth-monitoring devices form a more reasonable proportion of the cost of the heavier transportable equipment and would not normally be recommended for portable tools.

Mr. Lancaster must be commended on his maintenance policy. In view of this, the double earth connections should prove effective, particularly in a large factory where the permanent earth connections can be made reliable. However, having gone to the expense of providing two paths to earth, it seems a pity not to go the stage further and continuously monitor them. I am very much in sympathy with his views on well maintained 110-volt hand-lamps, but as Messrs. Hayes, Morris and Scott point out, there are good reasons for adopting the lower voltage. We changed gradually to 25-volt lamps, installing permanent transformers where this was warranted and using 110/25 volt 120-watt portable transformers elsewhere. The improvement in the life and output of the lamps was most noticeable.

In reply to Mr. Morris, I agree that there would be little difference in safety between the 240-volt and 110-volt Butcher systems provided that, in each case, the mid-point of the secondary of the isolating transformer was earthed through the trip coil. But if 240-volt tools with double-pole switching, already in use on normal supplies, were transferred to a Butcher installation, the increase in safety would be very great. If 110-volt tools are available, the Butcher system seems unnecessary except perhaps in the most hazardous areas.

About seven years ago we went through the same procedure as Mr. Lewitt to find non-interchangeable plugs and sockets. However, it is wrong that such a course should be necessary, and the advent of a British Standard that will permit domestic plugs to be banned from the factory area is much overdue. I regret that I know of no test leads incorporating certified h.r.c. fuses.

Mr. Currie's fire engine must surely be one of the largest items of transportable equipment to have a monitored earthed 240-volt supply! As one responsible for electrical services in a hospital, Mr. Emmett makes a valuable and interesting contribution, and in industry we can gain consolation from the thought that though equipment may run hot it is not usually boiled!

I agree with Messrs. Mounsten-Harrison and Hill that 110 volts d.c. would be very safe, but it is not popular, possibly because of supply and switching problems; and although the actual risk of shock is less, rather nasty burns can be received under fault conditions.

Mr. Rumfitt's recommendation for daily checks of earth continuity presents a high ideal, but few firms would feel that the loss of time entailed in returning all items of low-voltage portable equipment daily to a central store was warranted.

In reply to Mr. Thomas, in order to ensure that contractors use suitable and safe equipment one must (i) include as a term in the contract an undertaking that low-voltage tools will be used, (ii) provide a suitable supply, and (iii) check while work is in progress that the contract is honoured.

I agree with every point made by Mr. Sutton. His and Mr. Dew's comments on welding hazards are worthy of special note. I think that Mr. Evans has in mind 125 c/s when he refers to high-frequency equipment, and I believe that one firm produces 110-volt 3-phase tools operating at this frequency which have no commutators or slip rings. The safety here lies in the choice of the voltage (64 volts to earth) rather than in the frequency (see Fig. 1), and the scheme is attractive if one is starting with a completely new installation.

I would refer Mr. Rowson to Section 6.2.1 for the reasons behind the circuit of Fig. 10. Since both earth connections are permanently made to a wall-mounted device, it should be possible to make them completely reliable.

As implied by Mr. Evans and confirmed by Mr. Vivian, the possibility of an earth wire coming adrift and straying into contact with a live pin in the plug is a potent source of accidents at 240 volts. Mr. Allen's practical solution to this problem is fairly well known but all too rarely applied. His support, bearing in mind his considerable first-hand experience of 110 volts for tools and 25 volts for hand-lamps, is much appreciated. I think Mr. Allen answers his own query, since, without a good earth return on the welding set, welding current flows down the pilot and main earth cores and causes overheating of the trip coil and possibly the relay; a deposit of carbon probably forms on the inter-phase insulation and eventually a flashover occurs. The auxiliary contact *a*4 in Fig. 10 would obviate this, but there has been difficulty in persuading trip manufacturers to incorporate it as a standard fitting.

DISCUSSION ON 'SHORT-CIRCUIT FORCES ON TURBO-ALTERNATOR END-WINDINGS'*

NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 29TH NOVEMBER, 1955
RUGBY SUB-CENTRE, AT RUGBY, 30TH NOVEMBER, 1955

Mr. W. N. Kilner (*at Manchester*): The authors appear to believe, as I do, that it is not in the best interest of the customer for the modern large two-pole turbo-generators to be subjected to full-voltage sudden short-circuit tests.

The number of phase-to-phase faults recorded by the Central Electricity Authority, and given in Section 7 of the paper, is a very small percentage of the total number of generators on the C.E.A. system. In the latest report the number is given as 966. More than half of these are 25 or more years old. It is probable that none of the recorded faults was as severe as a full-voltage sudden 3-phase short-circuit at the machine terminals, and that severe damage to the generators did not occur in all cases, if any. It is also certain that many of the generators had never been subjected to a sudden short-circuit test before installation. Therefore,

* YOUNG, J. B., and TOMPSETT, D. H.: Paper No. 1683 S, July, 1954 (see 102 A, p. 101).

during the past 25 years, at least, manufacturers have shown that, in general, the majority of their machines are capable of withstanding service operating conditions, from the point of view we are now considering. If 10% of the bad faults recorded—and bad ones usually are recorded—are worse than a sudden 3-phase short-circuit at the machine terminals, and sufficiently bad to cause complete destruction of the winding, I estimate that this represents about two machines in a thousand. I would rather face the possible loss of two machines for six months, than risk reducing the operating life of a thousand by unnecessarily severe testing.

Many of the generators in operation at present, particularly the older ones, are connected direct to busbars, and do not have the additional protection afforded by the reactance of transformers. All large modern turbo-generators do have this protection. We have tested well over 100 two-pole generators, including four 60 MW hydrogen-cooled machines, on sudden short-circuit at full voltage, and therefore believe that we have had ample opportunity to study their behaviour under such conditions. As a result I stated in the London discussion on the paper that the severity of the short-circuit forces on machines of the order of 100 MW and above were approaching the limit. Since then we have made a sudden short-circuit test on a 125 MVA hydrogen-cooled two-pole turbo-generator, and some permanent distortion of the end-windings did occur. This in itself was not serious, and the affected parts of the end-winding were re-blocked. However, on the final high-voltage test, following the short-circuit, a breakdown occurred on one half-coil at the point where the coil leaves the core. There was no permanent distortion of this coil near the point of breakdown, but we concluded that the heavy mechanical force to which it had been subjected was the cause of the breakdown. After removing the faulty half-coil, the rest of the winding withstood the high-voltage test. The winding had been subjected to a higher-voltage test before the short-circuit.

This faulty half-coil represented considerably less than 1% of the whole winding, and although the remainder withstood the final voltage test, it is unlikely that it is in such good condition as it was before the short-circuit test. The sudden short-circuit test is usually one of the last items in the testing programme, and any breakdown which occurs at this stage results in delay in the shipment of the machine, which is embarrassing to the manufacturer and the customer.

In dealing with the problem of satisfactorily supporting the windings, the designer must consider the type of coil insulation which is to be used. He may use a solid hard insulation which will not compress or permit any movement but is likely to crack under heavy mechanical pressure. Alternatively, he may use a flexible insulation which will not crack under pressure but would permit excessive movement, which cumulatively could be very large and might then result in failure of the insulation owing to bending. In general, manufacturers adopt a type of insulation which is a compromise between hard and flexible.

Two other points which make the larger machine less able to withstand short-circuit forces are as follows:

(i) Their voltages are higher and the insulation must be thicker, and therefore more liable to compress and permit movement.

(ii) The higher currents demand that the conductors shall have smaller laminations to prevent excessive eddy currents, and the conductors are therefore mechanically weaker.

I am not in favour of model tests, mainly because of the expense, which must eventually be paid for by the customer.

Mr. E. W. Connon (*at Manchester*): Empirical and unknown factors are, of course, not unusual in the study of the strength of structures, and there are many examples of their effects, varying from the Tay Bridge to the Comet air-liner. It is surprising, therefore, that the authors suggest a relaxation of proving tests. It has long been the tradition in the design of electricity supply systems to attempt to limit the spread of damage, by ensuring, as far as possible, that one piece of faulty equipment will not cause consequential damage to another. It would only be good engineering practice to depart from this principle if it were shown that it would pay. In this instance it would be necessary to show statistically that the cost of a stator breakdown due to short-circuit plus the cost of the resulting outage, all multiplied by the probability of its occurrence during the life of the generator, was less than the extra cost of making the end-windings strong enough not to break down. The authors have made no attempt to do this, and bearing in mind that the cost of the outage of a 60 MW base-load set is about £1 000 per day, and that a rewind would take many weeks, I think it would be difficult to do so.

In testing structures, or the materials from which they are made, it is general practice to allow a factor of safety to the applied tests. It is suggested that factors of safety of less than unity should be used. The factor of safety proposed is, in fact, even less than it seems, for stator voltages may exceed the normal if, for instance, the automatic-excitation regulator fails on loss of load, or is out of service. In such conditions, the probability of faults occurring is greater than normal, and the short-circuit current also is greater than normal.

Improved methods of cooling enable larger outputs to be handled by the same frame size and thus impose higher end-winding stresses, and, incidentally, produce lower efficiencies. If this tends to result in machines which cannot stand full-voltage short-circuits without some damage, surely the whole matter wants reconsideration. The full-voltage short-circuit test allows no factor of safety and should certainly not be relaxed—at least as a type test.

The authors' experiments point the way to a stronger design of end-winding, and surely this is the proper aim of such investigations.

Mr. S. J. Morley (*at Manchester*): If there is any doubt about the safety of a large machine, the higher cost of a safer job is well worth while. The high cost of outage for repairs on plant of high merit places a premium on reliability. There is thus complete justification for the expense involved in the construction of the replica stator and the tests carried out on it.

Some consideration of the effects of automatic voltage regulators may well be worth while. I do not know whether 'field forcing' will be used with automatic voltage regulators on the 120–180 MW machines, but I assume that, for transient-stability reasons, it will. Have we enough information on the effect of field forcing on decrement? Admittedly the first cycle of fault current is not likely to be appreciably increased, if at all, by this. While the initial shock is obviously the most severe on the windings, the persistence and vibratory effect of the subsequent current is very destructive. This is well illustrated in Fig. 6 of the paper. In fact, this Figure suggests that the damage is due not so much to the initial shock as to the persistence of the vibratory forces. It would be interesting—and possibly instructive—to superimpose on Fig. 6 the current curve to see how the decrement of deflection is related to that of current.

The reactance of a machine is very largely dependent on the physical size of the machine—and not so much on its electrical capacity. In view of the evident difficulty of ensuring adequate strength for the end-windings, the necessity for obtaining the much higher outputs from a given frame size is therefore a feature in favour of the limitation of fault currents. In spite of the effect of frame size on reactance, fault levels will inevitably increase, and because of field forcing, decrement will be less marked. It is therefore increasingly essential that generator protective gear be maintained in the highest possible state of

reliability. Speed of operation of protective gear, including that of the field circuit-breaker and field suppression, is at present inadequate for the present problem—a clearance in 5 cycles is evidently inadequate. There is room for improvement, although it is not all a problem for the alternator designer. However, even if very-high-speed protection were assumed, the rate of collapse of the rotor field remains a major problem, and this is in the province of the alternator designer.

Mr. J. Hindmarsh (*at Manchester*): With reference to Section 4 of the paper, it is appreciated that the accurate representation of an electromagnetic machine on a scale model to give identical overall performance presents some considerable difficulty. In this particular case, however, we are only interested in the electromagnetic forces produced by the interaction of measurable currents and associated fluxes, and the resistance to motion afforded by the combination of copper, insulation and bracing. It would therefore seem possible to construct a dimensionally similar model with perhaps no greater difficulty nor more complicated mathematical treatment than that experienced in building satisfactory aerodynamic models. While agreeing that the insulation would be the most questionable factor in a scale representation, such a model would at least be a check on the calculation of forces and deflections, and the performance of different bracing arrangements.

If it is objected that each machine is inevitably different because of manufacturing difficulties in exact repetition of particular bracing arrangements, the same criticism could be levelled at the tests on the full-scale replica, or even type tests. If short-circuit tests have to be continued but customers can be persuaded to accept type tests, it would seem worth while to build a model of, say, one-tenth full size and compare its performance with the actual and calculated performance in the same way as was done in Fig. 4 using the full-scale replica. If it were to behave as well as the replica the financial saving in such a model and the release of the actual machine from this onerous test would appear to be a sufficiently attractive proposition to merit consideration of the above suggestion.

Mr. N. N. Hancock (*at Manchester*): The authors have shown that considerable movement of the end-windings occurs on sudden short-circuit at rated voltage, even though there may be little permanent deformation to indicate it. Presumably movements of the same order of magnitude will occur under fault conditions in a machine in service. After some years of operation, however, the drying out and ageing of the insulation will render it appreciably more brittle than it was when new, and movements of the same magnitude are far more likely to cause fracture of the insulation than during the works test. Sudden short-circuit tests thus provide no reliable indication that a machine will withstand faults in service. These tests are thus not only risky, as the authors have shown them to be, but of doubtful value. The nature of the ageing of insulation is not such that more severe tests would give the desired evidence of reliable service, whilst they would do even more damage. The authors' conclusion that a sudden short-circuit is undesirable as a routine test is certainly justified by the results of their tests.

Mr. P. G. Ross (*at Rugby*): The authors tend to give the impression that, owing to the increase in rating of two-pole turbo-alternators, the short-circuit forces on the end-windings will become greater in the future than they have been in the past and will present increasing difficulties to the designer. However, the larger ratings under consideration are obtained not by increasing the dimensions of the machine but by employing novel cooling techniques, e.g. direct conductor cooling. The magnetic loading of a turbo-generator is normally limited by saturation rather than by heating, so that the increased outputs can only be obtained by very much higher electric loadings. The per-unit sub-transient reactance is, other things being equal, proportional to the ratio of electric to magnetic loading, so that machines would be expected to have higher reactances in the future. Thus the short-circuit forces need not necessarily increase.

The authors make a plea for a reduction in the severity of the short-circuit test on account of the remote likelihood of faults at the generator terminals in the case of a generator which is solidly coupled to a step-up transformer. It should be remembered, however, that, even in this case, a solid short-circuit at the alternator terminals has been known to occur. Mr. Carfrae has mentioned one instance. It is perhaps a remote possibility but one which cannot be entirely dismissed.

We should not forget that the forces arising from a 3-phase short-circuit from rated voltage on open-circuit are less severe than can obtain in practice. Consider a generator operating on full load, rated power factor and 5% over-voltage, and subjected to a solid 3-phase short-circuit. If we assume a power factor of 0·8 and a stator-winding leakage reactance of 8%, the short-circuit forces are equivalent to those occurring on a short-circuit test from 10% over-voltage on open-circuit.

Consider now a generator operating on full load and on hand control. If the alternator should become disconnected from the system the machine voltage could rise by 40 or 50%. A solid fault at the terminals under these conditions would give rise to forces about twice as severe as during the short-circuit test from rated voltage on open-circuit. We could thus argue that, if a short-circuit test is performed, a useful compromise is to perform it at rated voltage on open-circuit, and we should think very hard before reducing the severity of the test.

Messrs. J. B. Young and **D. H. Tompsett** (*in reply*): We are interested to note from Mr. Kilner's contribution that, following the sudden short-circuit tests on a 125 MVA alternator, a coil broke down on high-voltage test although the windings withstood an even higher voltage prior to the application of the short-circuit. We agree entirely that, although the remainder of the coils withstood the high-voltage test, the windings and insulation could not be in as good condition as they were before the test. Our own experience completely bears this out.

In reply to Mr. Ross, Section 2.1 of the paper mentions the greater resultant forces where the physical size of the machine has had to be increased to obtain the higher output. Where this is obtained by improved heat transfer without increase in physical size, we agree with Messrs. Kilner and Ross there is no corresponding increase in short-circuit forces. We would refer Mr. Ross to the reply to Mr. Winfield's comments in the London discussion.

In presenting an argument from the user's viewpoint Mr. Connon has quoted the high cost of outage of large sets. This argument is, of course, a double-edged weapon, and we have stated in a previous reply our opinion that the customer should balance this cost against whatever value he attaches to the application of severe tests on production machines. Mr. Kilner emphasizes the improbability of failure in service in the light of the available statistics. In the same context, we have also commented previously on the misconception of our proposals which is held by those who believe that a reduced factor of safety would result if short-circuit tests were omitted. Both Messrs. Connon and Hindmarsh employ the expression 'type test', but we doubt whether Mr. Connon would extend his interpretation of this term to include the small-scale models which Mr. Hindmarsh discusses in his interesting contribution.

Mr. Morley's remarks on the significance of the decrement and the necessity for the highest possible speed of the protective equipment are worthy of attention by relay and switchgear engineers. We have referred earlier to the relationship between the size, rating and the reactance of modern machines.

We hope that many readers will reach the same conclusions as Mr. Hancock.

With all the experience accumulated over the years on works short-circuit tests, one would have thought that it would be possible to obtain agreement between manufacturer and customer on the proposed bracing by inspection, thus enabling alternators to be put into commission as new machines. The customer could then feel confident that a generator so installed would start its operating life with a higher insulation factor of safety than it would have had if a sudden short-circuit test had been applied. There is nothing revolutionary in this view, since it merely conforms with long-established American practice.

DISCUSSION ON 'TIMING THE OPERATION OF CONTROL SYSTEMS ASSOCIATED WITH ROTATING EQUIPMENT'* AND 'THE DYNAMIC BRAKING OF INDUCTION MOTORS'†

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, AT BIRMINGHAM, 12TH MARCH, 1956

Dr. E. Friedlander: It does not seem to be sufficiently clear from the paper by Dr. Harrison that the general rules expressed by eqns. (4)–(6) are not valid if saturation is taken into account. This is always necessary when dealing with dynamic braking of induction motors because it is easy to see that, without saturation, a normal motor would never be able to give a dynamic braking torque much beyond about one-sixth of its rated torque. The typical factor 2 in eqn. (6) is valid only for the completely unsaturated state, because it is due to the equal magnetizing and load currents, each being equal to $I_1/\sqrt{2}$. This rule breaks down in the presence of saturation, and the ratio of load current to direct current may even approach unity for the maximum torque with a very flat saturation characteristic. A proof of this is given in the Appendix to a paper published in 1949.‡

Fig. 6 of the paper by Messrs. Cuthbert and Picken indicates that the performance of the dynamic brake is far from what it could be if the reduction of resistances were accomplished at the correct rate. The ideal solution would obviously be a steady reduction of resistance as the speed decreases; this is in principle, possible to achieve by connecting a reactor in parallel with a suitably chosen fixed resistance. The combination then works analogously to the principle of the double squirrel-cage induction motor. Whether this solution is economically justified would probably want further investigation, but I should be interested to know whether the method has been contemplated.

Mr. R. W. Newby: The primary importance of the brake on a horizontal 2-roll mill is its value from the point of view of accident prevention. The fact that it is also used to stop the rolls quickly in the course of production is incidental. It is therefore essential that the braking system should always be maintained at a high level of efficiency. For this reason I cannot agree that electromagnetic friction brakes are necessarily to be preferred to purely electrical systems. The friction brake is liable to suffer directly through wear of the brake linings or sluggishness in mechanical parts. Moreover, in many rubber factories considerable quantities of french chalk and other powders are present. Accumulation of this dust on the brake linings could very seriously impair the braking efficiency. Regular and thorough maintenance is therefore essential.

Messrs. C. Cuthbert and D. A. Picken (*in reply*): Dr. Friedlander's suggestion for improving the efficiency of braking systems could well be studied using the technique applied in the paper, but so far as we know no work has been done on it.

We would endorse the points made by Mr. Newby regarding the necessity for regular and thorough maintenance, but wide experience shows that the electromagnetic friction brake has proved more satisfactory than the electrical braking techniques which have, within our knowledge failed on several occasions.

Surprisingly, the contamination by french chalk and other powders does not seem to affect adversely the large number of brakes of which we have experience, nor does wear seem to be a difficult problem. Brakes are known to have operated for many months without the need for any adjustment whatsoever, despite frequent use.

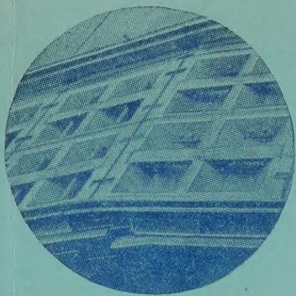
Dr. D. Harrison (*in reply*): I fully agree with Dr. Friedlander that saturation effects are of primary importance in dynamic braking, but the equations given in the paper are surely generally valid provided that the value of X_m corresponds to the degree of saturation. Perhaps this was not emphasized sufficiently in the paper.

Where the operating cycle demands frequent stopping and starting, electric braking is usually preferable to mechanical braking. Such operational braking should be clearly distinguished, however, from emergency braking, and I cannot agree with Mr. Newby that electric braking is sufficiently reliable for the latter purpose. In view of the possibility of supply failure a reliable mechanical system would seem to be necessary for the emergency braking of dangerous machines.

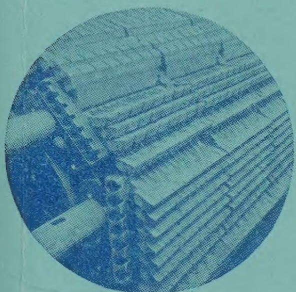
* CUTHBERT, C., and PICKEN, D. A.: Paper No. 1800 U, March, 1955 (see 103 A, p. 112).
† HARRISON, D.: Paper No. 1885 U, August, 1955 (see 103 A, p. 121).
‡ FRIEDLANDER, E.: 'Principle and Features of a New Dynamic Braking and Motor-Control System for A.C. Winders', *G.E.C. Journal*, 1949, 16, p. 204.

Proved Performance with the

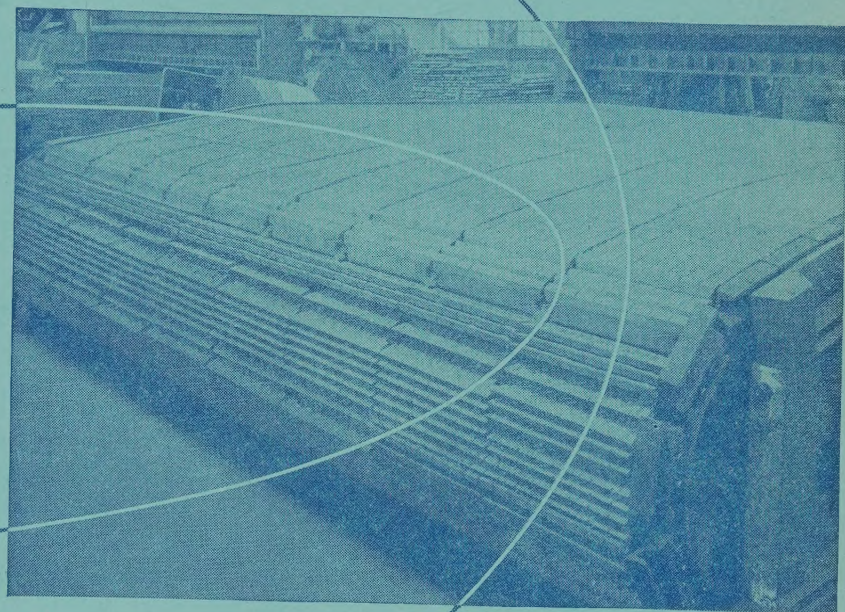
'L' Stoker



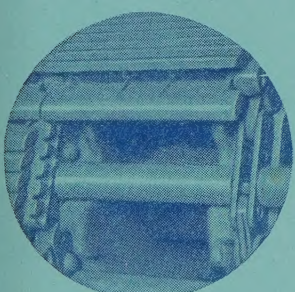
Close control of air supply gives even burning and allows fuels varying from refuse to anthracite to be used efficiently.



Automatic cleaning of fire bars, which are free to grow without affecting efficiency.



Parts requiring attention are easily accessible and renewable with minimum interference to stoker operation.



Stoker chains are distinct from grate surface so that each is free to perform its own function.

Progressive industries are choosing the 'L' type stoker on its outstanding performance. Operating with almost every available grade of fuel, it will fire every known design and type of water-tube boiler. It combines high efficiency with remarkably low maintenance. The proved performance of the 'L' type stoker has prompted many of Britain's newest factories to specify this equipment.

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Example.—Smith, J.: 'Overhead Transmission Systems', *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

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